

A Rapid Restoration Method for Infrared Aero-Optical Degraded Image of High-Speed Reconnaissance Aircraft

Yanqiao Zhao, Jiubin Tan, and Jian Liu

Center of Ultra-precision Optoelectronic Instrument Engineering, Harbin Institute of Technology, Harbin, China

Email: 420805314@qq.com

Abstract—In order to meet the requirement of rapidly deblurring aero-optical degraded image of high-speed reconnaissance aircraft, a rapid restoration method is proposed. By using a guide whose shape, size, and position information are unchanged in the reconnaissance images, the degraded function of the motion blurred image is effectively extracted, and then a inverse filter algorithm is employed to restore the blurred image. In our algorithm, all restoration works are finished only in five steps, so it greatly reduces computation time. A motion-blurred image with a resolution of 1600×1200 is restored only in 0.86s. The experimental results show that the proposed method has distinct advantages of fast computation and preferable effect.

Index Terms—Image Restoration; Infrared Image; Aero-Optical Degraded Image; Fast Algorithm

I. INTRODUCTION

Reconnaissance aircraft is one of the main reconnaissance tools in modern war [1]. In order to achieve goal of obtaining intelligence, a series of pictures will be got by camera equipped on aircraft. However, when reconnaissance plane travels at high-speed, aero-optical effect will occur. It makes the reconnaissance image blur and reduces the accuracy of investigation [2]. In order to keep reconnaissance ability and give consideration to real time investigating requirement, it is important to research on rapid restoration algorithm for reconnaissance image [3].

Traditional deblurred algorithms are iterations [4, 5], which take an iterative process that alternately optimizes the motion blur kernel and the latent image. The motion blur kernel and the latent image need to be calculated again and again, so the traditional deblurred method is not good for fast restoration. There are three ways to solve this problem.

The first approach is converting the serial computing mode into a parallel one [6, 7]. In this method, the works of optimizing the motion blur kernel and the latent image are simultaneously in different DSPs, and then the calculation results are exchanged, and used for the next optimizing period. It is effective for raising the frames per second of image restoration processing.

The second way is skipping some iterative points reasonably. An iterative accelerating technique based on linear search was presented in [8]. By estimating the next iterative result based on the current iterative result, some iterative points can be skipped, and the convergence rate can be improved. Iterative accelerating techniques based on vector extrapolation acceleration technique were presented in [9-11]. These methods don't require the minimization of a cost function, and achieve convergence rate improving. In [12], variance threshold was applied to assist sample selection, and not only redundant information was discarded by means of the sample selection algorithm, but a real-time model updating algorithm was also applied to speed up the restoration rate of serial images.

The third method is accelerating both latent image estimation and kernel estimation in an iterative deblurring process [13]. For latent image estimation, strong edges are predicted from the estimated latent image in the prediction step, and then solely used for kernel estimation. It allow us to avoid using computationally inefficient priors for non-blind deconvolution to estimate the latent image. For kernel estimation, the optimization function is formulated by using image derivatives rather than pixel. Working with image derivatives allows us to reduce the number of Fourier transforms from twelve to two, saving 5/6 of the computation required for calculating the gradient. This method runs an order of magnitude faster than traditional iteration, while the deblurring quality is comparable.

All the fast algorithms above make the calculating speed increase. However, iteration is not avoided fundamentally, so reduction of computation time is limited.

In Yixian Qian's method, both primary CCD and high-speed CCD are used [14-16]. During the exposure period of the primary CCD, the high-speed CCD captures sharp sequential images. Furthermore, the high-speed CCD and the primary CCD capture the image of the same target in the meantime, so the motion trail recorded by sharp sequential images captured by the high-speed CCD can completely represent that of the blurred image captured by the primary CCD. Point spread function of the image captured by the primary CCD is constructed rapidly by using the sequential images, and then a traditional method

like RL algorithm or Wiener filter algorithm is used to restore the motion-blurred image. Time cost of restoring every degraded image is less than the exposure period of the primary CCD, so the real time performance of this method is strong. The shortcoming is that it is a method applicable only under the hardware condition of high-speed CCD used to assist the primary CCD.

At present, celestial navigation has been widely used for aircraft [17]. In this navigation method, a distant object is selected as a guide. Based on the invariable location of the guide, course of aircraft can be determined by calculating azimuth and altitude of the guide relative to the aircraft [18, 19]. For reconnaissance aircraft, the course is unchanging, so the shape, size, and position of guide on reconnaissance image is invariant. It proves us a new restoration method for reconnaissance image. In this paper, we proposed a rapid method of restoring aero-optical degraded image for high-speed reconnaissance aircraft based on prior knowledge of guiding image, in our method, degraded function can be extracted from blurred image and then the degraded image can be restored. It will greatly reduce computing time because no iteration used. Experimental results are also given.

The main contributions of this paper are summarized as follows.

We propose a rapid method of restoring aero-optical degraded image for high-speed reconnaissance plane, and the algorithm proposed has advantages of fast computation and preferable effect.

By using a distant guide, a simple serial computing method consisting only five steps can be used to calculate degraded function. Comparing to iteration algorithms, the work of obtaining degraded function can be greatly accelerated.

The remainder of this paper is organized as follows: In Section II, the basic principle of our fast method of restoring motion blurred image is described. Simulation and applicable condition of the algorithm proposed are given in Section III. Section IV presents experiment results and related discussions. Finally, the paper is concluded in Section V.

II. BASIC PRINCIPLE

For reconnaissance aircraft which a infrared imaging system equipped on, the imaging process can be divided into two stages, one is the light reflected or radiated from object space pass through optical system, and the other is the optical signal is recorded by image sensor.

In the first step, the light in object space is disturbed because of aero-optical effect, and the optical signal on the surface of image sensor moves randomly. It can be presented as:

$$mid(x, y) = PSF(x, y) * in(x - s_x(t), y - s_y(t)) \quad (1)$$

where $mid(x, y)$ is the optical signal on the surface of the image sensor, and it is called middle image later, $PSF(x, y)$ denotes the point spread function of optical system, $in(x, y)$ represents optical signal in object space, $s_x(t)$ and $s_y(t)$ are trajectories of the optical signal in the x and y direction separately, $*$ denotes convolution operation.

For infrared image, the object space light is from high temperature object and from low temperature background. In the condition of a background such as the sky has the same environment temperature, the gray values of all parts of the background are the same, and there is no difference whether the background moves or not, so the object space light can be described as a dynamic target superimposed on a static uniform background:

$$in(x - s_x(t), y - s_y(t)) = in_1(x, y) + in_2(x - s_x(t), y - s_y(t)) \quad (2)$$

where $in_1(x, y)$ and $in_2(x, y)$ denote background and target separately.

Insert the Eq. 2 into the Eq. 1, the middle image can be described as:

$$mid(x, y) = PSF(x, y) * [in_1(x, y) + in_2(x - s_x(t), y - s_y(t))] \quad (3)$$

In the second step, the optical signal recording process is time integral average of optical signal during exposure time, so the recorded image can be described as:

$$out(x, y) = \frac{1}{t_e} \int_0^{t_e} mid(x, y) dt \quad (4)$$

where $out(x, y)$ is the final image, t_e denotes the exposure time of the image sensor.

Insert the Eq. 3 into Eq. 4, and the Fourier transform of Eq. 4 is:

$$OUT(f_x, f_y) = OTF(f_x, f_y) \cdot IN_1(f_x, f_y) + OTF(f_x, f_y) \cdot IN_2(f_x, f_y) \cdot H(f_x, f_y) \quad (5)$$

where $OTF(f_x, f_y)$, $IN_1(f_x, f_y)$, and $IN_2(f_x, f_y)$ are the Fourier transforms of $PSF(x, y)$, $in_1(x, y)$, and $in_2(x, y)$. f_x and f_y denote spatial frequency in the x and y direction separately. $H(f_x, f_y)$ represents the degraded function of the motion-blurred image, and it is:

$$H(f_x, f_y) = \frac{1}{t_e} \int_0^{t_e} e^{-i2\pi(f_x s_x(t) + f_y s_y(t))} dt \quad (6)$$

In Eq. 5, the degraded function $H(f_x, f_y)$ has a separable form, and if the product of $IN_1(f_x, f_y)$ and $OTF(f_x, f_y)$ can be subtracted, and then divided by the product of $IN_2(f_x, f_y)$ and $OTF(f_x, f_y)$, $H(f_x, f_y)$ can be separated from frequency spectrum of the degraded image.

For reconnaissance aircraft, the course is invariant during all flight process, so size, shape, and position information of the guide in reconnaissance images is unchanged. A clearly guiding image with a guide which is not affected by aero-optical effect can be obtained before the aircraft reach to high speed. In this condition, $s_x(t) = s_y(t) = 0$, and $H(f_x, f_y) = 1$, and Eq. 5 is:

$$OUT(f_x, f_y) \Big|_{s_x(t)=s_y(t)=0} = OTF(f_x, f_y) \cdot IN_1(f_x, f_y) + OTF(f_x, f_y) \cdot IN_2(f_x, f_y) \quad (7)$$

where $OUT(f_x, f_y)$ in Eq. 7 denotes the frequency spectrum of clear image with guide.

If no target exist, only background left, the target $in_2(x - s_x(t), y - s_y(t)) = 0$, and the Eq. 5 is:

$$OUT(f_x, f_y)|_{in_2=0} = OTF(f_x, f_y) \cdot IN_1(f_x, f_y) \quad (8)$$

The $OUT(f_x, f_y)$ in Eq. 8 represents the frequency spectrum of background.

According to Eq. 8, we can see that the product of $OTF(f_x, f_y)$ and $IN_1(f_x, f_y)$ can be got directly from background, and the product of $OTF(f_x, f_y)$ and $IN_2(f_x, f_y)$ can also be obtained by subtracting Eq. 8 from Eq. 7.

According to the analysis above, based on the prior knowledge of clear image with guide, the method of extracting degraded function $H(f_x, f_y)$ from degraded image is:

$$H(f_x, f_y) = \frac{OUT(f_x, f_y) - OUT(f_x, f_y)|_{in_2=0}}{OUT(f_x, f_y)|_{s_x(t)=s_y(t)=0} - OUT(f_x, f_y)|_{in_2=0}} \quad (9)$$

After obtaining $H(f_x, f_y)$, degraded image can be restored by using a inverse filtering or Wiener filtering algorithm. In order to reduce the time cost, the inverse filtering algorithm is chosen, and the algorithm of restoring degraded image can be described as:

$$f = F^{-1} \left(OUT \cdot \frac{OUT|_{s_x=s_y=0} - OUT|_{in_2=0}}{OUT - OUT|_{in_2=0}} \right) \quad (10)$$

where OUT , OTF , IN_1 , and IN_2 are short for $OUT(f_x, f_y)$, $OTF(f_x, f_y)$, $IN_1(f_x, f_y)$, and $IN_2(f_x, f_y)$ separately, and F^{-1} represents inverse Fourier transform.

There is no iterated operation and only five steps including a Fourier transform, a subtraction, a division, a multiplication, and an inverse Fourier transform in our method, so the algorithm proposed is good for reducing the operation time.

III. SIMULATIONS

A clear image with a resolution of 256×256 is shown in Fig. 1, and it consists of background and a lenna subimage. The gray level of the background can be chosen any value from 0 to 255 as long as the background is uniform, and 100 is chosen in this example. The lenna subimage is selected as a guide, and its resolution is 128×128 .

When reconnaissance aircraft flies at high-speed, not only aero-optical effect reduces the quality of images, but noise also affects the clarity of the images. A series of motion-blurred images degraded from the picture in Fig. 1 with different Gaussian noise variances are shown in Fig. 2, and the motion blur kernel is shown in the lower right corner of each picture. The degraded images are used to simulate the aero-optical degradation ones.



Figure 1. Undegraded image

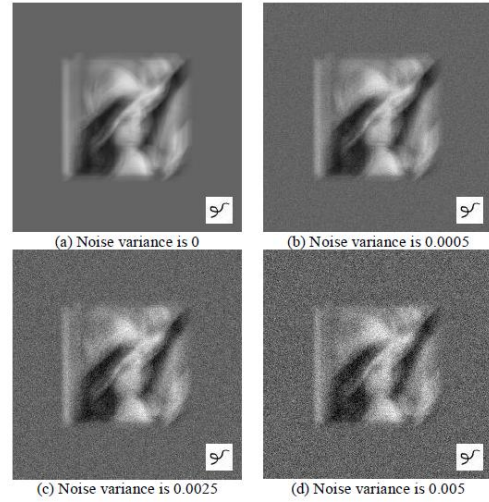


Figure 2. Degraded images for random motion with noise

In order to restore the degraded images in Fig. 2, we have to get backgrounds besides the clear prior image, and backgrounds can be obtained from the corresponding degraded images. Each background is a uniform image with a resolution of 256×256 , and the gray values of all pixels are equal to that of the pixel at the first row and first column of the corresponding degraded image.

After obtaining the backgrounds, the degraded images can be restored by the proposed method indicated in Eq. 10, and the restoration results are shown in Fig. 3.

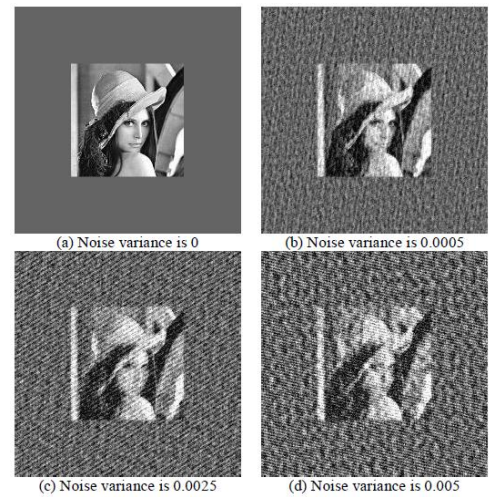


Figure 3. Restored images

From Fig. 3, we can see that as the noise variance increases, the ringing effects of the deblurred images are becoming more and more serious.

The correlation coefficient (CC) which shows the similarity of two matrixes can be used to evaluate the quality of the restored image, because the nature of image is a matrix. The CC is defined as:

$$r = \frac{\sum_{i=1}^M \sum_{j=1}^N (f_r(i, j) - \bar{f}_r)(f(i, j) - \bar{f})}{\sqrt{\sum_{i=1}^M \sum_{j=1}^N (f_r(i, j) - \bar{f}_r)^2 \sum_{i=1}^M \sum_{j=1}^N (f(i, j) - \bar{f})^2}} \quad (11)$$

where $f_r(i,j)$ and $f(i,j)$ are gray values of the i th row and j th column pixels of the restored image and the clear prior image, separately, $\bar{f}_r$ and $\bar{f}$ denote the average gray values of the restored image and the original image, separately, M and N represent the number of pixels in the x and y direction, separately.

According to Eq. 11, CCs of the clear prior image and the restored ones can be calculated, and the values are 1, 0.8336, 0.6664, and 0.5490, separately.

The result shows that the CC decreases with the increase of noise variance, and the restoration result is perfect when no noise exists. In order to demonstrate the regulation between CC and noise variance, correlation coefficient - noise variance curve is drew in Fig. 4.

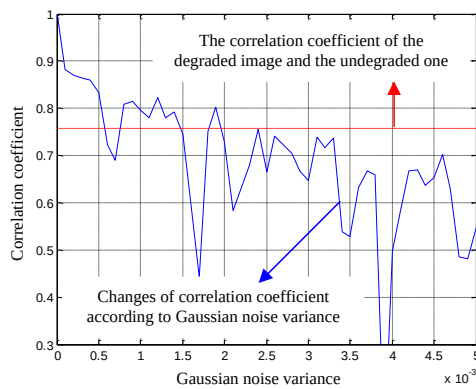


Figure 4. The CC - noise variance curve

In Fig. 4, the dashed line denotes the CC between the motion-blurred image without noise and the undegraded one, and the value of it is 0.7576. The solid line represents CCs between the restored images and the undegraded one. From solid line, we can see that the quality of the deblurred image is deteriorates with the noise variants increases. When the noise variance is less than 5×10^{-4} , the CCs is greater than 0.7576, this result suggests that quality of the degraded image can be improved by using our method. If the noise variance is in the range of 5×10^{-4} and 2.5×10^{-3} , the CCs hovers around 0.7576, this result shows that it is uncertain if the quality of the degraded image can be improved. When the noise variance is larger than 2.5×10^{-3} , the CCs is less than 0.7576, it suggests that our method doesn't apply to improve the quality of the degraded image. Based on the analysis above, it can be concluded that the condition of our method to improve the quality of motion blurred image is the noise variance superimposed on the blurred image must be less than 5×10^{-4} .

We monitored the time cost of the restoration method proposed. Our algorithm was run on a Samsung R440 computer, and the configuration of the R440 is shown in Tab.1.

TABLE I. TESTING ENVIRONMENT

CPU	Core I3-380M, 2.53GHz
Memory	2G DDR3 RAM
Graphics card	HD5470 graphics card
Operating system	Window 7 32bit home
Programming software	MATLAB R2012b

Ignoring the time cost of reading the image, it takes only 40ms to complete the restoration algorithm proposed. The result shows that the method proposed has the advantages of fast computation.

IV. EXPERIMENTS

In this part, two experiments have been finished to demonstrate the effectiveness of our method. In the first one, a motion-blurred guiding image was restored by using a clear guiding image. In the second one, a degraded image including guide was deblurred by using a clear guiding image.

A. Restoration of Motion-Blurred Guiding Image

We used China Wuhan Guide infrared IR113 imager whose exposure time is 40ms, and captured an undegraded image with a resolution of 768×576 . This picture is shown in Fig. 5 and used for image restoration later.



Figure 5. Undegraded infrared image

In Fig. 5, the face and neck is guide because the temperature of them is higher than that of the other parts, and the desk, the chair, the wall, the cloth etc have the same environment temperature, so these parts were selected as the background.

According to the linear shift invariant properties of the convolution, Eq. 1 can be described as:

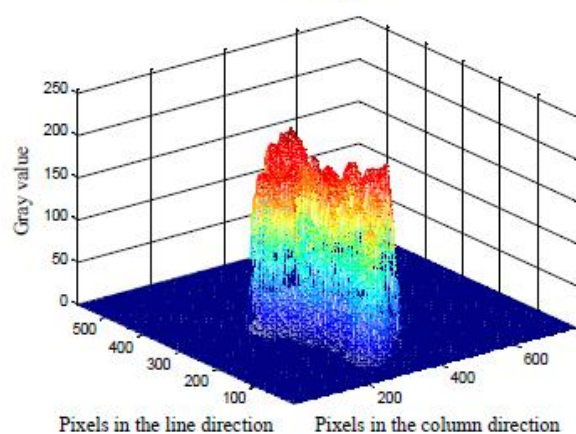
$$mid(x, y) = PSF(x - s_x(t), y - s_y(t)) * in(x, y) \quad (12)$$

Eq. 12 indicates that the degraded image from aero-optical effect is equal to the one due to vibration of the imaging system. In that case, a random moving camera can be used to simulate aero-optical effect. The camera was held in trembling hands, and the imaging parameters remained unchanged, a motion-blurred picture was captured and shown in Fig. 6.

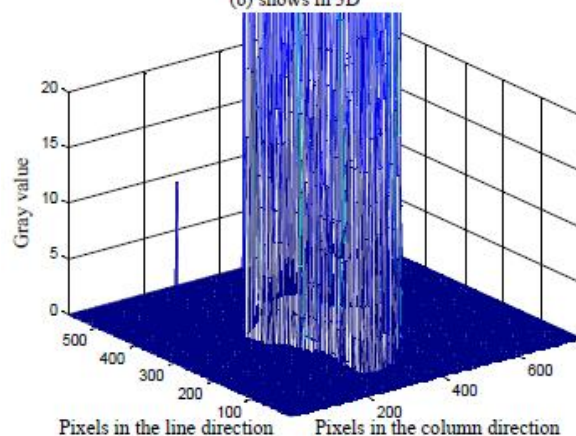
Fig. 6(a) is the degraded image shown in 2D, Fig. 6(b) is the 3D display of Fig. 6(a), and we can see that the background is nearly a flat surface. In order to see the background more carefully, a partial image is shown in Fig. 6(c), and a noise signal overlying on the background can be seen. Because only one pulse noise appears, and the gray value is less than 15, far less than the gray value of the guide, so the condition of noise variance less than 5×10^{-4} is met. According to the analysis in simulation part, a good restored image can be expected.



(a) shows in 2D



(b) shows in 3D

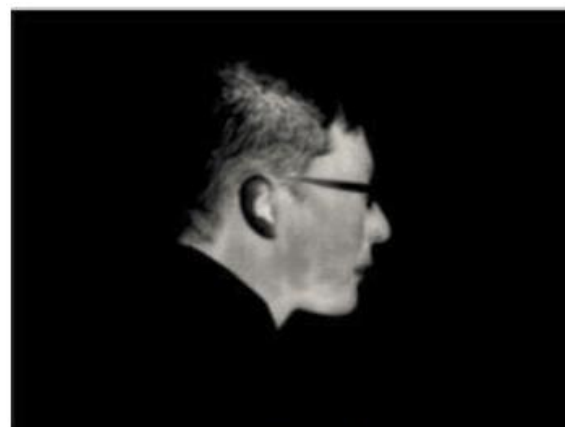


(c) partial display in 3D

Figure 6. Degraded infrared image

Correspond to the method in the simulation part, a background was obtained from Fig. 6(a). We got the gray value of the 1st row and 1st column pixel of the motion-blurred image firstly, and then a uniform picture with a resolution of 768×576 was constructed based on this gray value. This uniform image is the prior knowledge of the background.

By using the clear prior image in Fig. 5 and the background already constructed, the blurred image was restored by the method proposed, and it is shown in Fig. 7 (a). We can see that the motion-blurred image was restored clearly.



(a) our method



(b) S.Cho's method

Figure 7. Restored image

In order to evaluate the restoration effect quantitatively, we executed our method and an existing algorithm on the same hardware, and then compared them.

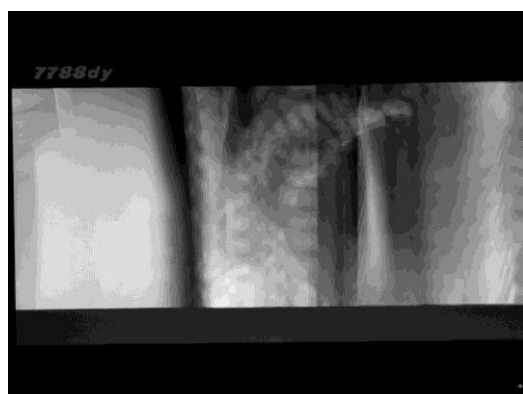
Among many restoration algorithms, S.Cho's method is selected because it is very mature and has been applied in the software of Photoshop CC, What's more, the S.Cho's algorithm can be applied to the same technical field as our method.

The restoration result by S.Cho's method is shown in Fig. 7(b). Comparing Fig. 7(a) with Fig. 7(b), we can see that our method made the edge of the restored image much sharper, it shows that there is no loss of the restoration effect by using our method.

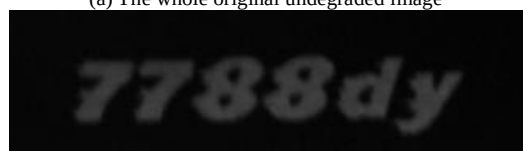
Comparing the time cost of our method and the S.Cho's one under the same testing environment shown in Tab.1, the results are 0.35s and 4.00s, separately, it can be concluded that the operating time can be reduced by 91.25% by using our algorithm. The advantage of fast computation of our algorithm is verified again by this experiment.

B. Restoration of Degraded Image Including a Guide

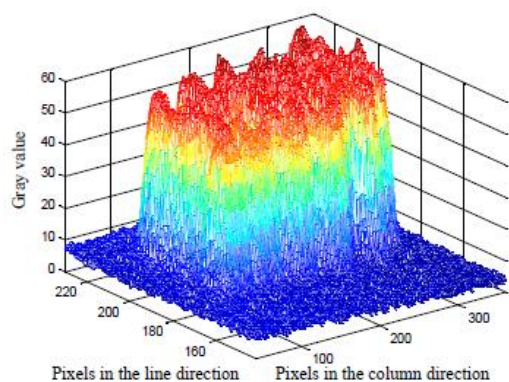
For reconnaissance aircraft, scenes which need to be investigated are unknowable, so prior knowledge of the complete image can't be obtained. But that of the guiding part can be got. In the following experiment, we would prove that the complete image can also be deblurred by using the prior knowledge of the clear guiding image.



(a) The whole original undegraded image



(b) TV logo and its neighborhood



(c) TV logo and its neighborhood shown in 3D

Figure 8. Original undegraded image

A reconnaissance picture can be divided into two parts, one is a time-unvarying part corresponding to the sky containing a guide, and the other is a time-varying part corresponding to the ground to be investigated. According to the characters above of the reconnaissance picture, a TV image can be used to simulate a reconnaissance image, because the black bar and the TV logo can be used to simulate sky and guide, separately, and the dynamic image below the black bar represents the time-varying reconnaissance scene. In the following experiment, a movie called I, ROBOT is used, and all pictures were captured by CANON A720 IS camera, the setting parameters of the camera is shown in table 2.

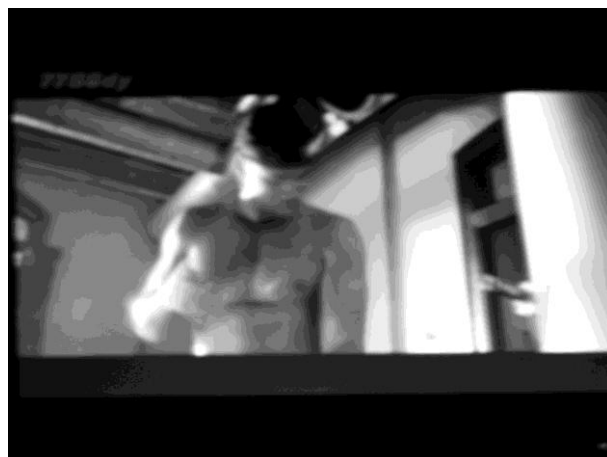
TABLE II. SETTING PARAMETERS OF CANON A720 IS

Resolution	1600×1200
exposure time	0.5s
ISO	80
F	2.8

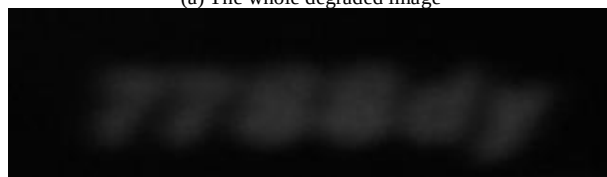
Firstly, a clear picture was captured and shown in Fig. 8, and it can be considered as the one imaged by the reconnaissance aircraft before it reaches to high speed.

Fig. 8(a) is the whole clear image, and in the upper left corner, there is a time-unvarying TV logo which was used as a guide. Fig. 8(b) is a magnified views of the

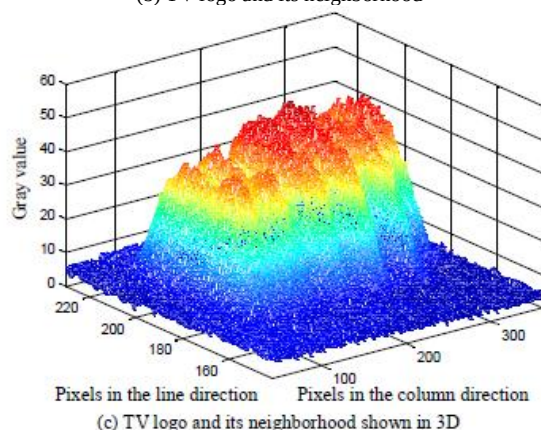
guide, and it is the pixels from the 141st to the 230th lines and from the 41st to the 360th columns of Fig. 8(a). Fig. 8(c) is the 3D view of the Fig. 8(b), we can see that the TV logo's neighborhood is not quite uniform, and some noise is overlying on the background.



(a) The whole degraded image



(b) TV logo and its neighborhood



(c) TV logo and its neighborhood shown in 3D

Figure 9. Degraded image

In order to capture an aero-optical degraded image, we kept the imaging parameters unchanged, and held the camera in tremble hands during imaging, and a motion-blurred picture was captured and shown in Fig. 9.

Fig. 9(a) is the complete degraded image, a magnified view of the guide is shown in Fig. 9(b), and it is the pixels from the 141st to the 230th lines and from the 41st to the 360th columns of Fig. 9(a). In Fig. 9(b), the word 7788dy can't be recognized clearly. Fig. 9(c) is the 3D view of the Fig. 9(b), it also shows that some noise is overlying on the background.

Because the backgrounds of the original subimage and of the degraded subimage are not uniform, and some noise overlying, based on the analysis before, we can forecast that the restoration result will not be perfect and the ringing effect will occur.

In order to extract the degraded function from degraded image, Fig. 8(b) and Fig. 9(b) were used, and a background was constructed based on the Fig. 9(b). The resolution of background is the same as the one of the Fig. 9(b), and the gray value of the background is equal to the one of the pixel at the 1st line and 1st column of the Fig. 9(b). We subtracted the background from the Fig. 8(b) and Fig. 9(b), separately, and then the first different was divided by the second one, degraded function was obtained.

The resolution of the degraded function is 320×90 , which is less than the one of the complete motion-blurred image. In order to deblurred the complete one in Fig. 9(a), the resolution has to be extent to 1600×1200 , which is equal to that of the Fig. 9(a).



(a) The whole restored image



(b) TV logo and its neighborhood

Figure 10. Restored image

Interpolation method such as nearest-neighbor interpolation, bilinear interpolation, or cubic interpolation can be used to extent resolution of the degraded function, In order to pursue less time cost, nearest-neighbor interpolation was selected because it has the advantages of high operation speed compared to other two methods.

The extended degraded function was used to restore the complete motion-blurred image shown in Fig. 9(a), and the restoration result is showed in Fig. 10.

Fig. 10(a) is the restoration result, we can see that the door, the arm, the window, etc have more clear edges comparing to the blurred one in Fig. 9(a). Magnified view of the guiding part which is the pixels from the 141st to the 230th lines and from the 41st to the 360th columns of Fig. 10(a) is shown in Fig. 10(b), and the word 7788dy can be recognized even if ringing effect occurred. It proves the effectiveness of our algorithm again.

In the testing environment which is the same as that in Tab.1, the time spent are only 0.86s, so it can be concluded that our algorithm have the advantage of fast computation.

In order to further improve the quality of recovery image, Wiener filter can be used instead of inverse filter, and the impact of noise will be degrade at the cost of increasing the running time to some extent.

If low-level programming language is used to improve the operational efficiency of the program, and the program runs in professional image processor like DSP or GPU accelerator, and the program work parallelly by using multiple threads technique, Operation time can be further reduced.

V. CONCLUSION

In summary, in order to meet the requirement of rapidly deblurring aero-optical degraded image of high-speed reconnaissance aircraft, a rapid restoration method is proposed. In our method, a guide whose shape, size, and position information is unchanged is used for restoration, and all deblurring work is completed only in five steps. It takes only 0.86s to restore an image with a resolution of 1600×1200 . The experimental results show that the proposed method has distinct advantages of fast computation and preferable effect.

ACKNOWLEDGMENT

This work was funded by national natural science foundation of China grants 61108052 and 61078049.

REFERENCES

- [1] Jing Zang, Hu Liu, Xianping Ni. Mission Simulation-Based Fighter Anti-ship Effectiveness Evaluation on Stealth Capability. *Journal of Multimedia*, 2013, 8(6) pp. 720-725.
- [2] Zhang tian-xu, Hong han-yu, Zhang Xin-yu. Aero- Optical Effect Correction: Principles, Methods and Applications: *Precision-Guided Munitions and Human Suffering in War*. Press of University of Science and Technology of China, 2014.
- [3] Junfang Tang, Xiandan Xu. Adaptive Super-Resolution Image Reconstruction Algorithm of Neighborhood Embedding Based on Nonlocal Similarity. *Journal of Multimedia*, 2014, 9(2) pp. 261-268.
- [4] Wang Feng, Zhang Kunfan, Meng Fankun, Zhao Yongjun. A Turbulence-Degraded Image Restoration Algorithm Using the Maximum Likelihood Estimation Method. *Applied Mechanics and Materials*. 2014, 543 pp. 2391-2394.
- [5] Hanyu Hong, Liangcheng Li, Tianxu Zhang. Blind restoration of real turbulence-degraded image with complicated backgrounds using anisotropic regularization. *Optics Communications*. 2012, 285 pp. 4977-4986.
- [6] Hong Han-yu. Research on Parallel Restoration Method for Infrared Detect Turbulence-degraded Images. *Infrared Technology*. 2009, 31(1) pp. 57-60.
- [7] Hong Hanyu, Zhang Xiuhua. Parallel Method for Restoration of Turbulence degraded Image. *Computer & Digital Engineering*, 2009, 37(3) pp. 164-166.
- [8] Hong Han-Yu, Wang Jin, Zhang Tian-Xu. Study on Acceleration Technique of Circulation Iterative Restoration Algorithm for Infrared Target Images. *Journal of Infrared and Millimeter Waves*, 2008, 27(1) pp. 115-118.
- [9] D. S. C. Biggs, M. Andrews. Acceleration of iterative image restoration algorithms. *Applied Optics*, 1997, 36(8) pp. 1766-1775.

- [10] Li Yong, Fan Cheng-yu, Shi Dong-feng, Wang Haitao, Feng Xiaoxing, Qiao Chunhong, et al. Turbulence-Degraded Image Blind Restoration Method Using Accelerated and Damped Richardson-Lucy Algorithm. *Laser & Optoelectronics Progress*, 2011, 48 pp. 081001.
- [11] Li Yong, Fan Cheng-yu, Shi Dong-feng. Atmospheric Turbulence-Degraded Image Blind Restoration Method Using the Accelerated and Regularized RL Algorithm. *Journal of Atmospheric and Environmental Optics*. 2011, 6(5) pp. 342-350.
- [12] Li Ming and Yang Jie. Image Acceleration Restoration Algorithm for Turbulence-Degraded Images Based on Support Vector Machine. *Journal of Infrared and Millimeter Waves*, 2009, 28(6) pp. 472-475.
- [13] Sunghyun Cho and Seungyong Lee. Fast Motion Deblurring. *ACM Transactions on Graphics*, 2009, 28(5) pp. 145.
- [14] Yixian Qian, Fangrong Hu, Xiaowei Cheng, Weimin Jin, et al. Real-Time Image Deblurring by Optoelectronic Hybrid Processing. *Applied Optics*, 2011, 50(33) pp. 6184-6188.
- [15] Yixian Qian, Yong Li, Jie Shao, Hua Miao, et al. Real-Time Image Stabilization for Arbitrary Motion Blurred Image based on Opto-Electronic Hybrid Joint Transform Correlator. *Optics Express*, 2011, 19(11) pp. 10762- 10768.
- [16] Y Qian, H Miao, J Shao, W Jin, et al. Real-time restoration of an image blurred by arbitrary motion using an optoelectronic hybrid joint transform correlator. *Journal of Optics*, 2011, 13(8) pp. 085403.
- [17] Wang Yu, Wu Zhiqiang, Zhu Xinhua. Satellite Formation based on SDDF Method. *Journal of Networks*, 2014, 9(4) pp. 986-992.
- [18] Jared Perkins, Tyler Wills, Amy Underwood, May Win Thein. Dynamic Implementation of the Celestial Navigation (CelNav) Technique for Extraterrestrial Surface Navigation. *AIAA/AAS Astrodynamics Specialist Conference*. 2012.
- [19] Ning Xiaolin, Huang Panpan, Fang Jiancheng. A New Celestial Navigation Method for Spacecraft on a Gravity Assist Trajectory. *Mathematical Problems in Engineering*, 2013, 2013 pp. 950675

Zhao yanqiao received his B.S. from Harbin Institute of Technology in 2006, M.S. from Harbin Institute of Technology in 2008. Currently he is pursuing his PhD degree in Harbin Institute of Technology. His research interests are dynamic optical transfer function and motion-blurred image restoration.

Tan jiubin received his B.S., M.S. and Ph.D from Harbin Institute of Technology in 1982, 1987 and 1991 separately. Currently he is a professor in Harbin Institute of Technology. His research interest is Ultra precision measurement technique and Instrument Engineering.

Liu jian received his B.S. from Southwest Jiaotong University in 1997, received his M.S. and Ph.D from Harbin Institute of Technology in 2002, 2009 separately. Currently he is a professor in Harbin Institute of Technology. His research interests are Diffraction optics and photoelectric measuring and testing.