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

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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 an 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 alternatingly
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 form 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:

\[
\text{mid}(x, y) = \text{PSF}(x, y) \ast \text{in}(x-s_x(t), y-s_y(t))
\]  
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 form 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:

\[
im(x-s_x(t), y-s_y(t)) = \text{in}_1(x, y) + \text{in}_2(x-s_x(t), y-s_y(t))
\]  
where \text{in}_1(x,y) and \text{in}_2(x,y) denote background and target separately.

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

\[
\text{mid}(x, y) = \text{PSF}(x, y) \ast [\text{in}_1(x, y) + \text{in}_2(x-s_x(t), y-s_y(t))] 
\]  

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:

\[
\text{out}(x, y) = \frac{1}{t_e} \int_0^{t_e} \mid \text{mid}(x, y)dt
\]  
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:

\[
\text{OUT}(f_x,f_y) = \text{OUT}(f_x,f_y) \ast \text{IN}_1(f_x,f_y) \ast \text{IN}_2(f_x,f_y) \ast \text{H}(f_x,f_y)
\]  
where OUT(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. \text{H}(f_x,f_y) represents the degraded function of the motion-blurred image, and it is:

\[
\text{H}(f_x,f_y) = \frac{1}{t_e} \int_0^{t_e} e^{-2\pi j (f_x s_x(t) + f_y s_y(t))}dt 
\]  
In Eq. 5, the degraded function \text{H}(f_x,f_y) has a separable form, and if the product of \text{IN}_1(f_x,f_y) and \text{OUT}(f_x,f_y) can be subtracted, and then divided by the product of \text{IN}_2(f_x,f_y) and \text{OUT}(f_x,f_y), \text{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 \text{H}(f_x,f_y)=1, and Eq. 5 is:

\[
\text{OUT}(f_x,f_y) = \text{OUT}(f_x,f_y) \ast \text{IN}_1(f_x,f_y) \ast \text{H}(f_x,f_y)
\]  
where \text{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:
\[ \text{OUT}(f_x, f_y) = \text{OTF}(f_x, f_y) \cdot IN_1(f_x, f_y) \] (8)

The \( \text{OUT}(f_x, f_y) \) in Eq. 8 represents the frequency spectrum of background.

According to Eq. 8, we can see that the product of \( \text{OTF}(f_x, f_y) \) and \( IN_1(f_x, f_y) \) can be got directly from background, and the product of \( \text{OTF}(f_x, f_y) \) 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:

\[ H(f_x, f_y) = \frac{\text{OUT}(f_x, f_y) - \text{OUT}(f_x, f_y)}{\text{OUT}(f_x, f_y) - \text{OUT}(f_x, f_y)} \] (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:

\[ f = F^{-1}(\text{OUT} \cdot \frac{\text{OUT}[m_n]}{\text{OUT} - \text{OUT}[m_n]}) \] (10)

where \( \text{OUT}, \text{OTF, IN}_1, \) and \( \text{IN}_2 \) are short for \( \text{OUT}(f_x, f_y) \), \( \text{OTF}(f_x, f_y) \), \( \text{IN}_1(f_x, f_y) \), and \( \text{IN}_2(f_x, f_y) \) 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 but also 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.

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 resorted image, because the nature of image is a matrix. The CC is defined as:

\[ r = \frac{\sum_{i=1}^{M} \sum_{j=1}^{N} (f(i, j) - \bar{f})(\hat{f}(i, j) - \bar{\hat{f}})}{\sqrt{\sum_{i=1}^{M} \sum_{j=1}^{N} (f(i, j) - \bar{f})^2} \sqrt{\sum_{i=1}^{M} \sum_{j=1}^{N} (\hat{f}(i, j) - \bar{\hat{f}})^2}} \] (11)
where \( f(i,j) \) 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. \( \bar{f}_x \) and \( \bar{f}_y \) 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.

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 768x576. This picture is shown in Fig. 5 and used for image restoration later.

![Undegraded infrared image](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:

\[
\text{mid}(x, y) = \text{PSF}(x - s_x(t), y - s_y(t)) \ast \text{in}(x, y)
\]  

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.

![Motion-blurred image](image)

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![Motion-blurred image](image)

In Fig. 6, the 3D display of Fig. 6(a) 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 \( 5 \times 10^{-4} \) is met. According to the analysis in simulation part, a good restored image can be expected.

<table>
<thead>
<tr>
<th>TABLE I. TESTING ENVIRONMENT</th>
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<tbody>
<tr>
<td><strong>CPU</strong></td>
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<tr>
<td><strong>Memory</strong></td>
</tr>
<tr>
<td><strong>Graphics card</strong></td>
</tr>
<tr>
<td><strong>Operating system</strong></td>
</tr>
<tr>
<td><strong>Programming software</strong></td>
</tr>
</tbody>
</table>

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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.

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 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

<table>
<thead>
<tr>
<th>Resolution</th>
<th>1600x1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>exposure time</td>
<td>0.5s</td>
</tr>
<tr>
<td>ISO</td>
<td>80</td>
</tr>
<tr>
<td>F</td>
<td>2.8</td>
</tr>
</tbody>
</table>

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 141$^{\text{th}}$ to the 230$^{\text{th}}$ lines and from the 41$^{\text{st}}$ to the 360$^{\text{th}}$ 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.

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 141$^{\text{th}}$ to the 230$^{\text{th}}$ lines and from the 41$^{\text{st}}$ to the 360$^{\text{th}}$ 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.

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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).

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 14th 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.

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