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Heuristic optimization in penumbral image for high resolution reconstructed image[a)]

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Penumbral imaging is a technique which uses the fact that spatial information can be recovered from the shadow or penumbra that an unknown source casts through a simple large circular aperture. The size of the penumbral image on the detector can be mathematically determined as its aperture size, object size, and magnification. Conventional reconstruction methods are very sensitive to noise. On the other hand, the heuristic reconstruction method is very tolerant of noise. However, the aperture size influences the accuracy and resolution of the reconstructed image. In this article, we propose the optimization of the aperture size for the neutron penumbral imaging. © *2010 American Institute of Physics.* [doi:10.1063/1.3483211]

I. INTRODUCTION

Penumbral imaging is a technique which uses the fact that spatial information can be recovered from the shadow or penumbra that an unknown source casts through a simple large circular aperture.[1] Since such an aperture can be "drilled" through a substrate of almost any thickness, the technique can be easily applied to highly penetrating radiation such as neutrons[2–4] and other rays. In particular, neutron imaging is a key technique in laser fusion experiments because the neutron images can provide direct information about the burn region.

In neutron penumbral imaging, the aperture size is larger than the target size for the deconvolution. The main factors distorting the spatial resolution are nonisoplanarity due to the aperture and the noise contained in the penumbral image. Since penumbral imaging is based on a linear deconvolution technique, the aperture point spread function (PSF) should be sufficiently isoplanar (space-invariant). Moreover, the reconstruction is sensitive to the noise. On the other hand, for effective imaging of neutrons, the aperture should be thick enough to block neutrons in order to provide sufficient image contrast. Several apertures such as a toroidal-segment aperture have been proposed[5] and used for neutron penumbral imaging. Though these apertures can provide a reasonably sharp PSF, it is impossible to obtain a satisfactory isoplanar PSF over a large field of view, and the penumbral image usually contains Poisson noise with a low signal-to-noise ratio (SNR). The heuristic reconstruction method[2,6] is a powerful approach to neutron penumbral imaging because it can be used for a space-variant imaging system and is also very tolerant of the noise. However, the aperture size may distort the spatial resolution of reconstructed image. Therefore, we should obtain the optimum aperture size for neutron imaging. In this article, we propose to obtain the optimum aperture size by using a Wiener filter and the heuristic method, respectively.

II. NEUTRON PENUMBRAL IMAGING AND ITS RECONSTRUCTION

A toroidal segment aperture for neutron penumbral imaging is shown in Fig. 1. L_1 and L_2 are the distances from source object to aperture and from aperture to detector, respectively. $(L_1+L_2)/L_1$ is the magnification of the camera. The encoded image consists of a uniformly bright region surrounded by a penumbra (hatched region). Information on the source is encoded in this penumbra. It is easy to show that the encoded image $P(x,y)$ is given by Eq. (1)

$$P(x,y) = \int\int A(x,y,x',y') \cdot O(x',y')dx'dy', \tag{1}$$

where $A(x,y)$ is the aperture function or PSF; $O(x,y)$ is the function describing the source, respectively. If the PSF on the aperture is isoplanar (space-invariant), the penumbral image can be written as a convolution of the source function (O) and the PSF (A) as

$$P(r) = \int\int A(r-r') \cdot O(r')dr' = A * O, \tag{2}$$

where * denotes the convolution. Thus, given $P(x,y)$ and $A(x,y)$, the source function $O(x,y)$ can be reconstructed by a simple linear deconvolution technique. Usually, the deconvolution (reconstruction) is performed by using a Wiener filter[7] to reduce noise amplification. A toroidal segment for an ap-

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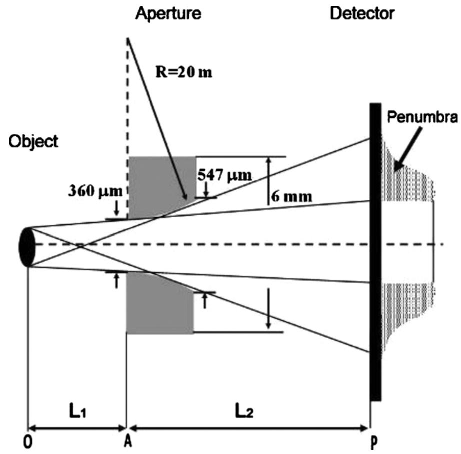


FIG. 1. The basic concept of neutron penumbra imaging. (in the case of aperture size=180 μm).

erture taper can provide better isoplanarity. The aperture is made from a tungsten (W) block of 6 cm in thickness. The principle of the toroidal segment for aperture taper is that rays drawn from various positions in a source plane are cut off in a similar way at the aperture. However, some distortion will still be introduced because it is impossible to obtain a perfect isoplanar PSF.

III. HEURISTIC RECONSTRUCTION METHOD

The reconstruction of a penumbral image can be viewed as an optimization problem. Our goal is that the cost function is minimized. The cost function to obtain the optimum solution is defined by[8]

$$E(\hat{O}) = \|P - \hat{P}\|^2 + \lambda \|L(\hat{O})\|^2, \tag{3}$$

where $\hat{P}$ is an estimated penumbral image and $\hat{O}$ is an estimated source object. The second term acts as a constraint operator. L is the Laplacian operator used here to obtain a "smooth" estimate. λ is a parameter to balance the first term and the second term. λ always takes a positive value. If λ is too large, the reconstructed image is too smooth, which means the spatial resolution of the reconstructed image is decreased. On the other hand, if λ is too small, the reconstructed image is noisy due to the noise effect. It can be seen that the method can obtain the optimum solution, even if the calculation is not linear, such as with ray tracing.

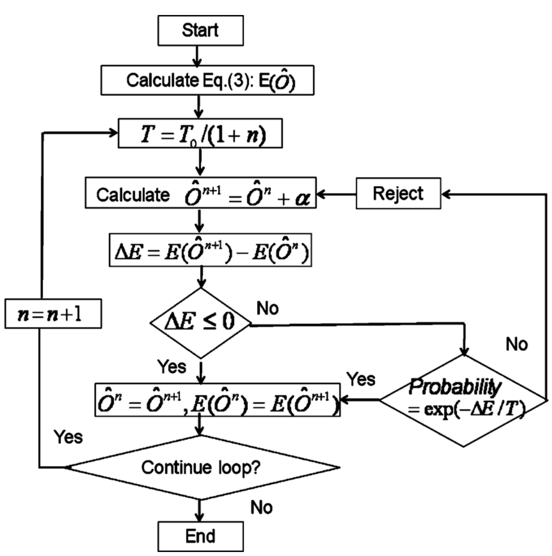


FIG. 2. The flowchart of the heuristic reconstruction method in the neutron penumbral imaging.

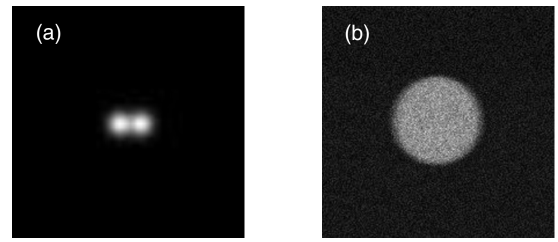


FIG. 3. The (a) source image and (b) penumbral image with Poisson noise.

There are many methods which can be used to minimize Eq. (3). Instead of the conventional gradient method, we used a heuristic method. The heuristic method is a search technique (or "approach to solving problems") applying principles of artificial intelligence such as genetic algorithm or simulated annealing (SA).[6,8] A property of the heuristic method is that the optimum solution can be obtained from any initial estimates. We used SA for this case. SA is an optimization technique based on calculation of state function in statistical mechanics. The technique can be applied to any minimization or learning process based on successive update steps (indeterministic) where the update step size is proportional to an arbitrarily set parameter which can play the role of temperature.

A flowchart of SA for reconstruction of neutron penumbral images is shown in Fig. 2. At first, the source image is estimated. The cost using Eq. (3) is computed. The estimated source image ($\hat{O}^n$) is then perturbed to generate a new estimated image ($\hat{O}^{n+1}$). The costs $E(\hat{O}^n)$ and $E(\hat{O}^{n+1})$ are then calculated for $\hat{O}^n$ and $\hat{O}^{n+1}$, respectively. T is a control parameter known as temperature which is decreased with increasing annealing cycles. T_0 is an initial temperature and n is the number of annealing cycles. Thus, the system is less likely to accept drastic changes at later cycles, thereby finetuning the result.

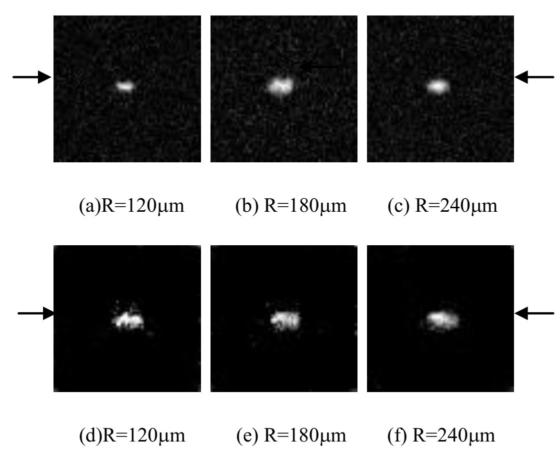


FIG. 4. Simulation results: (a)–(c) are results by the Wiener filter. (d)–(f) are results by the heuristic method.

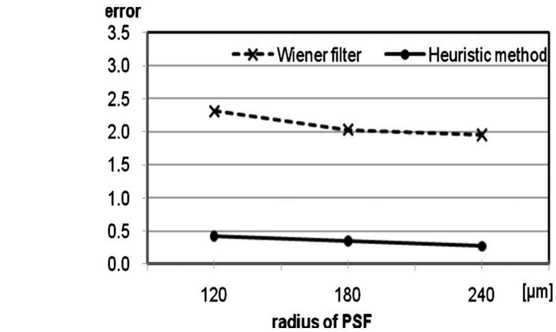


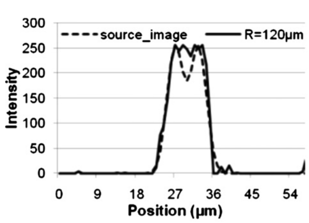
FIG. 5. Errors of reconstructed image with Wiener filter or heuristic method (SA).

IV. COMPUTER SIMULATION

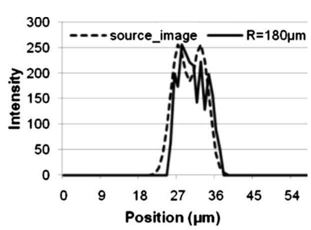
In order to verify the relation among the aperture size, the reconstruction accuracy, and the resolution of image, a computer simulation was carried out. The source image used in the computer simulation is shown in Fig. 3(a). Here, the source image has two small Gaussians and the target size is 19 μm. Figure 3(b) shows its penumbral image with the Poisson noise, which is obtained from the source image. We assumed that a neutron yield is 10^{11}. The distance from the object to the aperture ($=L_1$ in Fig. 1) is 12 cm and the object-detector distance ($=L_1+L_2$ in Fig. 1) is 120 cm. Thus, the SNR of the penumbral image is about 7 dB. In the computer simulation, we changed the radius of the aperture from 120 to 240 μm and evaluated the reconstructed images by the Wiener filter and the heuristic method, respectively.

Reconstructed images are shown in Fig. 4. When R (radius of the aperture) is small, it can be seen that there are distortions in each reconstructed image [in Figs. 4(a) and 4(d)] by Wiener filter and heuristic method compared with a large R [in Figs. 4(c) and 4(f)].

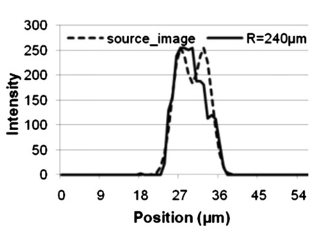
The reconstruction accuracy of both methods was assessed by comparison of image error between the reconstructed image and source image. Its result is shown in Fig.



(a)



(b)



(c)

FIG. 6. Profiles of source image and reconstructed image with the heuristic method. (a) $R=120$ μm, (b) $R=180$ μm, and (c) $R=240$ μm.

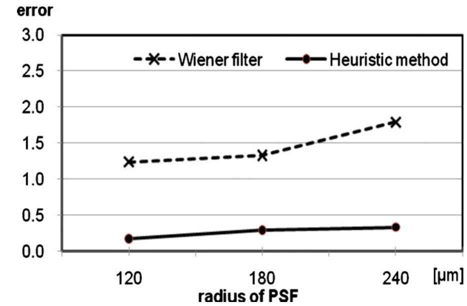


FIG. 7. (Color online) Errors of horizontal profile by Wiener filter or heuristic method.

5. In order to make quantitative evaluation, a root mean square error between the reconstructed image and the source image is used. From the results, when the size of PSF is larger, error of reconstructed image is more reduced. Moreover, the image errors in the reconstructed images are significantly improved by the heuristic method. It can be seen that the reconstruction by heuristic method is better than the one by the Wiener filter. Therefore we can see that the larger aperture size can produce clear reconstruction.

The horizontal profiles of reconstructed images by the heuristic method are shown in Fig. 6. As the size of aperture (R) is getting smaller, it matches the profile of the source image. Figure 7 shows errors between its profile and the source image's profile. We can see that there is less error by using a smaller aperture, between the profile of the source image and the profile of the reconstructed image.

In order to make a quantitative evaluation, we calculated the errors in the profiles of the Wiener filter and the heuristic method. It can be seen that when the R is large, the image error is small. However, when the R is small, the error in profile is large. Moreover, the heuristic method is very robust and produces a smaller error compared with the Wiener filter. From these results, when $R=180$, we can obtain a clear reconstructed image with high resolution.

In conclusion, we can see the heuristic method can obtain better results compared with the Wiener filter even if the aperture size is changed. By the use of this approach, we can set the optimum aperture for the experiments and also obtain better reconstructed images.

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