Complex Optical Component Measurement with Ptychography

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ABSTRACT

The extended Ptychography iterative engine (ePIE) has the advantages of fast convergence and high imaging accuracy, and is widely used in quantitative phase imaging. In the measurement process of complex optical components, the coherent diffraction imaging may get stuck in local optima and stop converging, resulting in incorrect reconstruction results. To increase the convergence speed, a hybrid algorithm method was proposed, which improves convergence speed and reduces computation time. The principle of this method is the mixed reconstruction of Ptychographic iterative engine (PIE) and ePIE. By adjusting the proportion of PIE and ePIE in iterative calculations, the probe and the object can be reconstructed to the global optimal value simultaneously. In the experiment, a random phase plate with a minimum structure size of 9.6×9.6 micrometers was measured. The experimental results demonstrate that compared to the ePIE algorithm, this algorithm can significantly improve convergence speed and converge to global optima. This article proposes an accelerated convergence method based on Ptychography, which provides a solution for high-precision and complex distributed object measurement.

Keywords: complex optical component, optical measurement, extended Ptychographic iterative engine

1. INTRODUCTION

Coherent diffraction imaging (CDI) obtains the absorption contrast and phase contrast information of the sample through iterative methods. In 1972, Gerchberg [1] and Saxton [2] proposed the first iterative phase recovery algorithm, abbreviated as Gerchberg-Saxton (G-S) algorithm. Fienup proposed the Hybrid Input and Output (HIO) algorithm and Error Reduce (ER) algorithm [3] in 1978 and 1982 to improve convergence speed. The single frame CDI algorithm using only domain and intensity constraints can result in non-unique reconstruction results. In 2004, Rodenburg and Faulkner proposed the ptychography iterative engine (PIE) algorithm based on full field scanning[4]. By scanning the overlapping areas and adding constraints, the unique solution of the reconstruction algorithm is ensured. In 2009, Maiden proposed the extended ptychography iterative engine (ePIE) algorithm [5], which added updates to the illumination and overcame factors such as uncertainty and instability of the illumination, greatly improving the reconstruction accuracy. The ePIE algorithm has become one of the most important techniques in diffraction imaging due to its high precision and robustness. With the deepening of research, researchers have improved experimental efficiency and reconstruction accuracy by improving the optical path [6][7][8], optimizing the illumination probe [9][10], and adding error correction methods [11][12] and so on.

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The measurement of complex optical components has always been an important research direction in the field of optical measurement, and its measurement methods mainly include interferometry and non-interferometry. For measuring objects with high transmittance and strong scattering, coherent diffraction imaging method is usually required.

2. METHOD

2.1 PIE system

The experimental structure of PIE is shown in Figure 1. In this structure, parallel beam is converged by a lens into an illumination probe. After being modulated by object information, the illumination probe is propagated to the CCD camera plane to form a diffraction image. By moving the 2-D mobile platform, a series of diffraction intensity images are obtained. Reconstructing object and illumination information through algorithms.

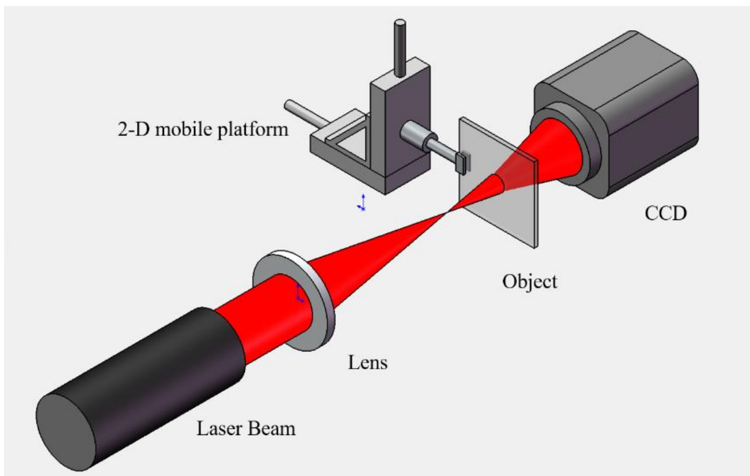

Figure 1. Structure of PIE experiment.

2.2 Principle of Ptychography

The PIE algorithm is iterative based, with the following main steps:

1) Assuming the complex amplitude distribution of the object being measured at any position n as $O_n(x,y)$, and the complex amplitude of the illumination as $P(x,y)$;
2) The exit wavefront of the object plane can be expressed as $\Psi(x,y) = O_n(x,y)P(x,y)$;
3) The wavefront information obtained by the CCD is $\Phi = \Im\{\Psi(x,y)\}$, $\Im\{\}$ as the forward wavefront transmission;
4) Using the diffraction intensity image obtained by detector I_n to update the amplitude of $\Phi(x,y)$, $\Phi'(x,y) = \sqrt{I_n}\frac{\Phi(x,y)}{|\Phi(x,y)|}$;
5) The wavefront $\Phi'(x,y)$ is transmitted in reverse to the object plane to obtain an updated exit wavefront of the object plane, $\phi(x,y) = \Im^{-1}\{\Phi'(x,y)\}$, $\Im^{-1}\{\}$ as the wavefront reverse transmission;
6) Update object complex amplitude information,

$$O_{n+1}(x,y) = O_n(x,y) + \frac{P(x,y)}{P_{max}(x,y)}\frac{P^*(x,y)}{|P(x,y)|^2+\alpha}\beta[\phi(x,y) - \Psi(x,y)] \tag{1}$$

α and β are constants that determine the convergence speed of the algorithm, with a value range of (0,1];

7) Move the scanning position to the next aperture and repeat the above update steps until the error converges.

The PIE extends the field of view of CDI to infinity, but due to the influence of complex amplitude of illumination, the algorithm cannot achieve good reconstruction results.

By reconstructing the illumination, ePIE has replaced PIE as one of the most important coherent diffraction imaging recovery algorithms. After updating the complex amplitude of the object in step 6), synchronously update the illumination $P(x, y)$.

$$P(x,y) = P(x,y) + \frac{O(x,y)}{O_{max}(x,y)} \frac{O^*(x,y)}{|O(x,y)|^2 + \alpha} \beta[\phi(x,y) - \Psi(x,y)] \tag{2}$$

In ePIE algorithm, the initial value of the illumination will determine the convergence speed, and it is usually necessary to guess the value of the illumination to be close to the true value. For objects with simple structures, the initial guess of the illumination only needs to be set as a Gaussian function. For the measurement of complex optical components, due to their complex and random structural distribution, it can greatly affect the convergence speed and even cause convergence to stop.

2.3 Main principle of hybrid algorithm

To improve the convergence speed of ePIE for the measurement of complex optical components, a hybrid algorithm is proposed. Firstly, we perform preliminary calibration on the illumination. By iterating the CDI algorithm on a diffraction image that has not been modulated by the object, the initial value of the illumination light can be reconstructed. Here, it can be approximated that the obtained illumination is close to the true value, and this illumination is input into the algorithm for PIE algorithm iteration. Ultimately, the object information under the initial illumination light will be obtained and converged to the local optimal solution. Finally, the ePIE iteration between the illumination light and the measured object will be performed, and the algorithm will converge to the global optimal value.

3. EXPERIMENT

3.1 Experimental parameters

In the experiment, a random phase plate with a manufacturing accuracy of 9.6×9.6μm was measured. In this experiment, the distance between the random phase plate and the CCD camera was 37.26mm. The minimum pixel size of the CCD was 2.4μm, with a bit depth of 8-bit. Each diffraction image had a size of 3600×3600 pixels and a scanning step size of 0.2mm. In the experiment, a total of 81 diffraction intensity patterns were captured. Figure 2 shows a diffraction image in the experiment.

Figure 2. Diffractive image.

3.2 Reconstruction results

In the algorithm, 50 PIE iterations are performed first, followed by 150 ePIE iterations. Figure 3 shows the reconstruction results after 200 iterations. We can see that the algorithm can clearly reconstruct the complex amplitude results of the illumination and the random phase plate.

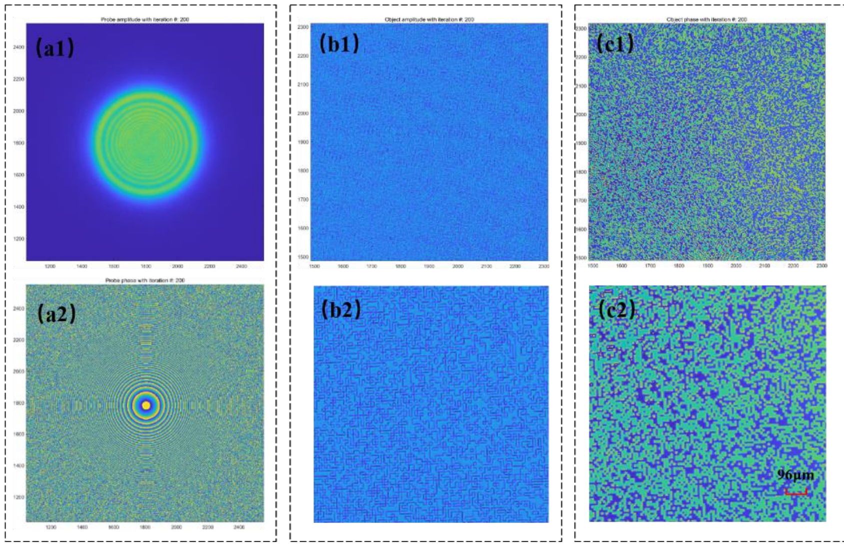

Figure 3. Results by algorithm reconstruction. (a1) and (a2) as the amplitude and phase of illumination of the object plane, (b1) and (b2) as the amplitude of random phase plate, (c1) and (c2) as the phase of random phase plate.

If only for the ePIE reconstruction, even if the initial guess is true, it will still cause the loss and blurring of illumination information in the initial few iterations, greatly affecting the convergence speed. Adopting a hybrid iterative algorithm can avoid this problem. From the reconstruction results, the hybrid convergence algorithm can significantly improve the convergence speed and converge to the global optimum.

3.3 Resolution verification

To verify the reconstruction accuracy of the hybrid algorithm, an amplitude resolution target was measured. In this experiment, the scanning step size of the mobile platform was 0.3mm, and the resolution board was 32.6mm away from the CCD camera. A total of 49 diffraction images were captured. There were 20 iterations and Figure 4 shows the reconstruction results.

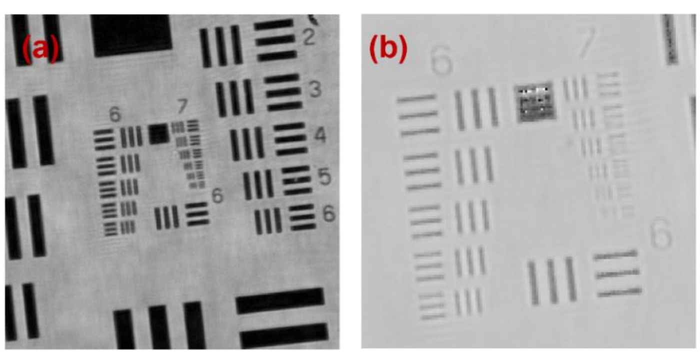

Figure 4. Experimental results. (a) as the amplitude of the amplitude resolution target, (b) as the phase of the amplitude resolution target.

From the reconstruction results, the ultimate resolution obtained is the element 4 of the group 7, which proves the accuracy of this method for reconstructing the 9.6μm random phase plate.

4. CONCLUSION

The ePIE algorithm reconstructs the complex amplitude information of the object and illumination through iterative methods. The initial guess of illumination can significantly affect the convergence process. Usually, we need to set the illumination as an ideal spherical wave. For the measurement of complex optical components, its complex structural distribution may lead to slow convergence speed or even halt.

In this article, we propose a hybrid reconstruction algorithm based on PIE and ePIE. Firstly, input an approximate true value of illumination to perform PIE algorithm iteration. Secondly, after PIE algorithm iterating to the local optimal value under the initial illumination, the ePIE algorithm is iterated to obtain the global optimal values of the measured object and the illumination. It is easy to obtain the initial value of illumination light. We can use a CCD camera to obtain a diffraction image without object, and transmit it to object plane through this image; and it can be directly generated through neural networks or other methods.

In the experiment, we reconstructed a random phase plate with an etching accuracy of 9.6 × 9.6 microns. To verify whether the reconstruction resolution of this method, we reconstructed the amplitude type resolution board and obtained an accuracy of the element 4 of the group 7. As a result, this hybrid algorithm can significantly improve the convergence speed and achieve high-precision measurement.

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