A fast converging and error reducing phase retrieval algorithm for Fourier Ptychographic microscopy

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Abstract: Fourier ptychography is a recently developed computational framework for wide-field, high-resolution imaging. Here, we propose to use a fast converging and error reducing phase retrieval algorithm to retrieve the complex sample information.
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1. Introduction

The applications of non-diffraction limited imaging or high-resolution images are widespread. It is known that the resolution limit of a conventional imaging system is defined by the numerical aperture (NA) of the objective lens. To obtain high resolution images, various approaches have been proposed. Owing to its superior properties and diverse applications, e.g. seeing through occlusions, per-pixel focus control, improved signal to noise ratio and improved depth information from focus/defocus, the synthetic aperture imaging technique is widespread [1]. In principle, the synthetic aperture technique combines multiple images to expand the field of view (FOV) and improves the image resolution.

Fourier Ptychography (FP) is an extended version of synthetic aperture imaging that captures complex light field using a non-interferometric setup [2]. FP iteratively stitches together many variably illuminated, low-resolution intensity images in the Fourier space to expand the frequency spectrum and thus recovers a high-resolution complex sample image. It is shown in [2] that rather than measuring the phase information (i.e., using interferometric setups), FP uses an iterative phase retrieval algorithm to recover the complex information of the sample.

A slow convergence is one of the major problems in retrieving the phase information, therefore, we propose a fast converging and an error reducing algorithm based on a combination of the conventional error reduction (ER) and the hybrid input–output (HIO) algorithm, which we refer to as ER/HIOA [3].

2. Fourier Ptychography and Phase retrieval algorithm (ER/HIOA)

The schematic setup of Fourier Ptychography is shown in Fig. 1. As depicted, FP consists of a Light Emitting Diode (LED) array and a conventional microscope with an objective lens.

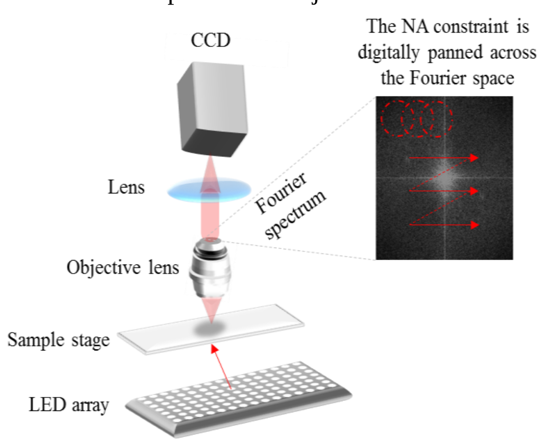

Fig. 1. Fourier Ptychographic imaging setup [2].

This LED array is used (see Fig.1) to illuminate the sample and for every single LED illumination one low resolution intensity image is recorded at the Fourier plane. Under the thin-sample assumption [2], each recorded image uniquely maps to a different passband i.e., allows certain range of sample's spectrum to propagate through the system. The FP algorithm then recovers a high-resolution complex image by alternatively constraining its amplitude to match the acquired low-resolution image sequence and its spectrum to match the panning Fourier constraint [2]. It is known that the imposed panning Fourier constraint expands the passband in the Fourier space and thus sharing its root with the aperture synthesis imaging technique [2]. Furthermore, both the FP and the conventional ptychography share the strategy of phase retrieval technique, i.e., iteratively seeking a complex sample solution that is consistent with many intensity measurements. It is known that slow convergence is one of the major problems of conventional phase iterative algorithms [3]. Therefore, in this work, in order to improve the convergence, we propose a combined error reduction and the hybrid input-output algorithm to iteratively retrieve the complex measurements from the sample. Implementation of ER/HIOA is shown in Fig. 2. In our simulations, HIO algorithm is applied as follows [3],

$$f_{k+1}(x,y) = \begin{cases} \left|f(x,y)\right| e^{i\theta'_k(x,y)}, & \textbf{\textit{otherwise}} \\ f_k(x,y) - \beta f'_k(x,y), & (x,y)\in\gamma' \end{cases} \tag{1}$$

where the parameter γ indicates the region where the pixel values are 0 in the object image $\left|f(x,y)\right|$. The algorithm for ER differs from the HIO [see Eq. (1)], in that the $(k+1)^{th}$ iteration of the ER is presented by [3],

$$f_{k+1}(x,y) = \begin{cases} \left|f'_k(x,y)\right|, & \textbf{\textit{otherwise}} \\ 0, & (x,y)\in\gamma' \end{cases} \tag{2}$$

where once again γ includes all points at which the k^{th} approximation of the object image $f'_k(x,y)$ violates the object extent constraints. During the phase retrieval process, ER [i.e., Eq. (2)] is first performed with a number of iterations followed by the classical HIO [i.e., Eq. (1)], which is performed with several iterations. This combination (cycle) is then repeated as necessary. The combination of ER/HIO algorithm has been found to work better than using either just ERA or HIOA, and, as will be shown, results in a more accurate object and phase information being retrieved.

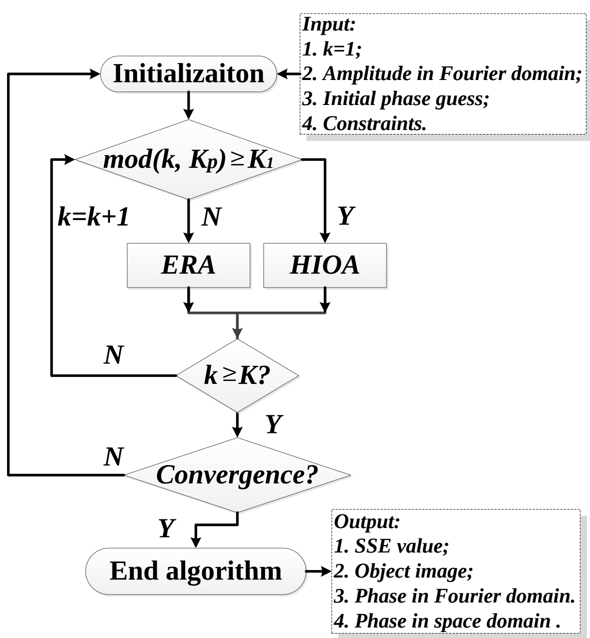

Fig. 2. Illustration of performing ER/HIO algorithm for FP reconstruction.

The FP reconstruction procedures are processed as follows: It starts with estimating a high-resolution spectrum of the given sample, $\hat{U}_0(k_x, k_y)$. This sample spectrum estimation will be sequentially updated with the low-resolution intensity measurements I_{mi}, where 'I' stands for low-resolution image, subscript '*m*' refers to measurements and '*i*' denotes the i^{th} LED. For each update step, a small sub-region of $\hat{U}_0(k_x, k_y)$ is selected corresponding to the optical transfer function (OTF) of the objective lens. We then applied FFT to generate a new low-resolution target image $\sqrt{I_{Ii}e^{i\varphi_{Ii}}}$. By using this, we can replace the target image's amplitude component i.e., $\sqrt{I_{Ii}}$ with the square root of the measurement $\sqrt{I_{mi}}$ to form an updated low-resolution target image $\sqrt{I_{mi}e^{i\varphi_1}}$. Later, this image is used to update its corresponding sub-region of $\hat{U}_0(k_x, k_y)$. We note that the replace-and-update sequence is repeated for all intensity measurements and we iterated several times until final solution is converged i.e., at which point $\hat{U}_0(k_x, k_y)$ is transformed to the spatial domain to produce a high-resolution complex sample image.

3. Simulation Results

Simulation results obtained from our series of computations are presented in this section. As shown in Fig. 3, FP can offer wide-field, high-resolution imaging of the complex wave-field.

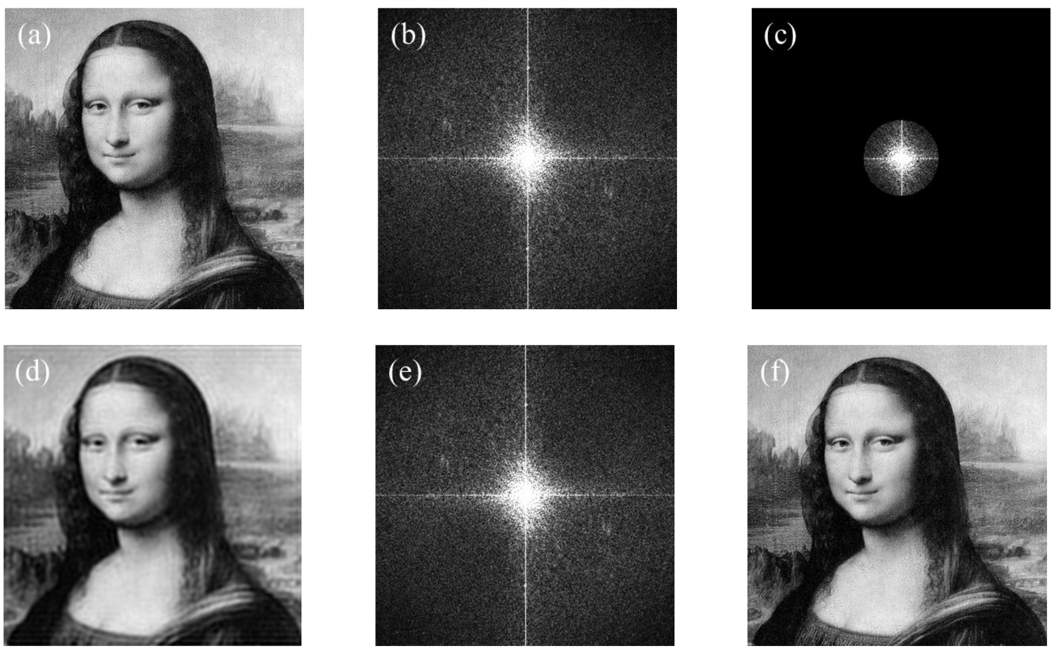

Fig. 3. Simulation results: (a) Primary high resolution intensity image, (b) Fourier spectrum of (a), (c) pupiled Fourier spectrum, (d) recovered low-resolution intensity image from (c), (e) iteratively recovered (performing ER/HIOA) full Fourier spectrum, and (f) retrieved (reconstructed) high resolution image (PSNR = 45.21 dB).

The applications of FP are diverse, for instance, this technique may potentially free clinicians manually moving the sample to different regions for observation [2].

4. References

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