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Sining Chen, Tingfa Xu, Jizhou Zhang, Bo Huang, Xing Wang, "Optimized fast spectral sampling for adaptive Fourier ptychographic microscopy ," Proc. SPIE 10420, Ninth International Conference on Digital Image Processing (ICDIP 2017), 104201P (21 July 2017); doi: 10.1117/12.2281558

SPIE. Event: Ninth International Conference on Digital Image Processing (ICDIP 2017), 2017, Hong Kong, China

Optimized fast spectral sampling for adaptive Fourier ptychographic microscopy

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ABSTRACT

The conventional Fourier ptychographic microscopy (FPM) is a computational imaging approach, which stitches together a sequence of low-resolution (LR) images captured by different angles illumination. However, the limitation of processing efficiency in capturing LR images is gradually becoming obvious. Utilizing the principle, aimed at reducing the amount of captured measurements and decreasing acquisition time, this paper proposes an optimized spectral sampling scheme. In this method, the importance of the spectra in the spectrum domain is analyzed and the more informative parts are selected. The acquisition efficiency can be increased because the selected images are captured and applied into the conventional FPM routine. Compared with the conventional FPM, experimental results significantly indicate that the redundancy of information and the time of image collection could decrease without debasing the quality of the reconstruction.

Keywords: Fourier ptychographic microscopy, optimized spectral sampling, image reconstruction, acquisition time

1. INTRODUCTION

Recently, Fourier ptychography (FP) as a phase retrieval technique has been received increasing attention, because it makes a breakthrough on high-resolution (HR) and large field-of-view (FOV) imaging [1], [2]. However, this method cannot capture large space-bandwidth product (SBP) images by a single shot. It only can sequentially capture and combine a set of low-resolution (LR) sample images whose resolution is defined by the objective lens' numerical aperture (NA), under different angles illumination. Because each LR image represents different spatial spectrum bands in the Fourier domain [3], a large SBP can be achieved by stitching. As a result, a high-resolution (HR) complex image can be reconstructed, which contains phase and amplitude information. Zheng et al. [1] has applied FP to microscopic and put forward Fourier ptychographic microscopy (FPM) lately. It uses an array of LED to generate different incident angles' light, which can image different components of the sample. The incident lights are seemed as plane waves and they can effectively expand the SBP and NA of the underlying optical system by stitching different shifts in special spectrum. This takes a long time to capture all angles' images needed to reconstruct a HR image. There have been various improvements and applications to solve this problem of FPM. For example, in order to reduce the acquisition time, mode expansion of the mutual coherence function has been reported, which just uses partially coherent LEDs [4]. And Dong et al. proposed a state-multiplexed routine to reduce the acquisitions [5]. In addition, turning on several multiplexed LEDs at one shot during collecting LR images demonstrated by Tian et al. [6] can decrease exposure time. They all have applied multiplexing illuminations to FPM. Bian et al. raised adaptive Fourier ptychography (AFP) [7] and Jiang et al. proposed Self-learning based FPM [8], which all utilize only the most important bands of the spectrum in Fourier domain. It has been proved that a HR image can be recovered through a part of each image that corresponding to a particular selection mode.

To solve the problem of efficiency and reduce the time of capturing and reconstructing images, this paper researches the spectrum redundancy in the Fourier domain and presents an optimized fast spectral sampling method, which can reconstruct a HR image just utilizing the more important measurements. Compared with these methods, if the importance of the spatial spectrum can be measured before acquisition, the data collection time will be decreased.

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Ninth International Conference on Digital Image Processing (ICDIP 2017), edited by Charles M. Falco, Xudong Jiang
Proc. of SPIE Vol. 10420, 104201P · © 2017 SPIE · CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2281558

2. PRINCIPLE

2.1 Redundancy in Fourier domain

Because images with different plane wave illuminations are equivalent to different spectrum regions in the Fourier domain, the reconstruction performance depends on a certain amount of data redundancy in both space and frequency domains. Intuitively, the data redundancy in frequency correspond to spectrum overlapping or spectrum sampling ratio of the object. As proposed in AFP, the redundancy in the Fourier spectrum [9] and spatial domain can rank the importance of the measurements. So, the data redundancy can be decreased by sacrificing the amount of LR images.

2.2 An optimized spectral sampling scheme

According to the AFP strategy, although this method which just updates the selected regions accelerates the reconstruction efficiency, it just reduces the reconstruction time but not data acquisition time. Therefore, considering the relationship between redundancy in Fourier distribution and the quality of the reconstruction, we now describe an optimized spectral sampling scheme aimed at reducing data collection time. First of all, we note that x-y and $k_x - k_y$ represent the spatial and Fourier domain. In addition, the incident angle θ_i can cause a frequency shift by

$$k_i = k\sin(\theta_i) = (2\pi/\lambda)\, n \sin(\theta_i) \tag{1}$$

In order to know the more important spectrum parts in advance, we must simulate the whole Fourier spectrum at first. It begins by capturing the most informative image illuminated by central LED and then transforming it into Fourier domain, just as $\sqrt{I}e^{i\varphi}, \varphi = 0$. Then, the spectrums of other low-resolution images are simulated by different phase shifts based on the central image spectra as

$$F\ (k-k_x, k-k_y) = F\ (I_c(x_i, y_i)e^{j2\pi(\frac{k_x x_i}{M}+\frac{k_y y_i}{N})}) \tag{2}$$

Where M and N are the pixel numbers of the captured image; x_i and y_i are location of the LED; k_x and k_y are the shifts of the central spectrum and I_c represents the central image.

Next, an intensity threshold is set as a metric to distinguish the importance of the spectrum in Fourier domain. Finally, a newly formed spectrum just includes the parts, which are higher than the threshold, and only the reservations are determined to be captured sequentially and performed the conventional FPM reconstruction. That is, before capturing images, the informative parts should be selected.

3. RESULTS

As introduced in [7], a complex (lena and city) image is transformed into the Fourier domain with a threshold and the parts whose values are smaller than the threshold will be rejected. That is to say, these pixels are set to zero and an updated spectrum distribution is estimated. Next, this Fourier spectrum is transformed back into the spatial domain. Finally, the reset image is compared with the corresponding raw image by the root-mean square error (RMSE). After setting the small values to zero, the remaining parts of the whole images are called reserved ratio. The relationship between reserved ratio and RMSE is shown in Figure. 1, indicating the importance of measurements decreasing along the radial direction. Based on the decreasing curves in Figure. 1, we find that the importance of the different parts in the whole spectra may decide the number of captured images.

To validate the result of this scheme in iterative process of FPM, algorithm experiment has been made. The parameters of the prototype setup are similar to [1], with 8×8 LEDs. Before capturing all measurements, we just capture the central image and transform it into Fourier domain. We base the adaptive threshold on the amplitude of the simulated spectrum. The amplitude in the low-frequency direction will be higher than the threshold, so these parts will be reserved. Then, images of the positions corresponding to the reserved parts will be captured and updated in conventional FPM routine. We experimentally evaluate the performance of this scheme and conventional FPM. As is depicted in Figure. 2, optimized spectral sampling scheme works successfully. Figure. 2(a) is the LR raw image of human smear blood and Figures. 2(b1) is the result of conventional FPM. The recovered HR images and spectrums using optimized fast spectral sampling FPM are displayed in Figure. 2(b2)-2(b4) with reservation decreasing.

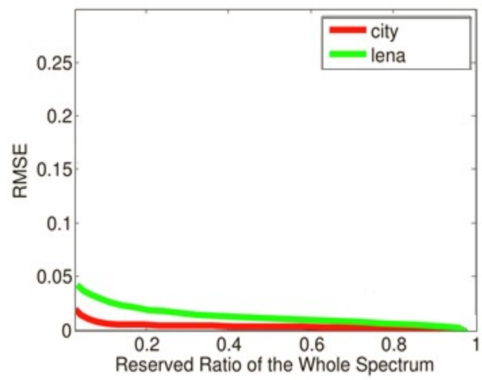

Figure. 1. Relationship between reserved ratio and RMSE and the simulation reconstruction results. The curves show decreasing trend along the reserved ration of the whole spectrum increasing, where RMSE shows the quality of the recovered image.

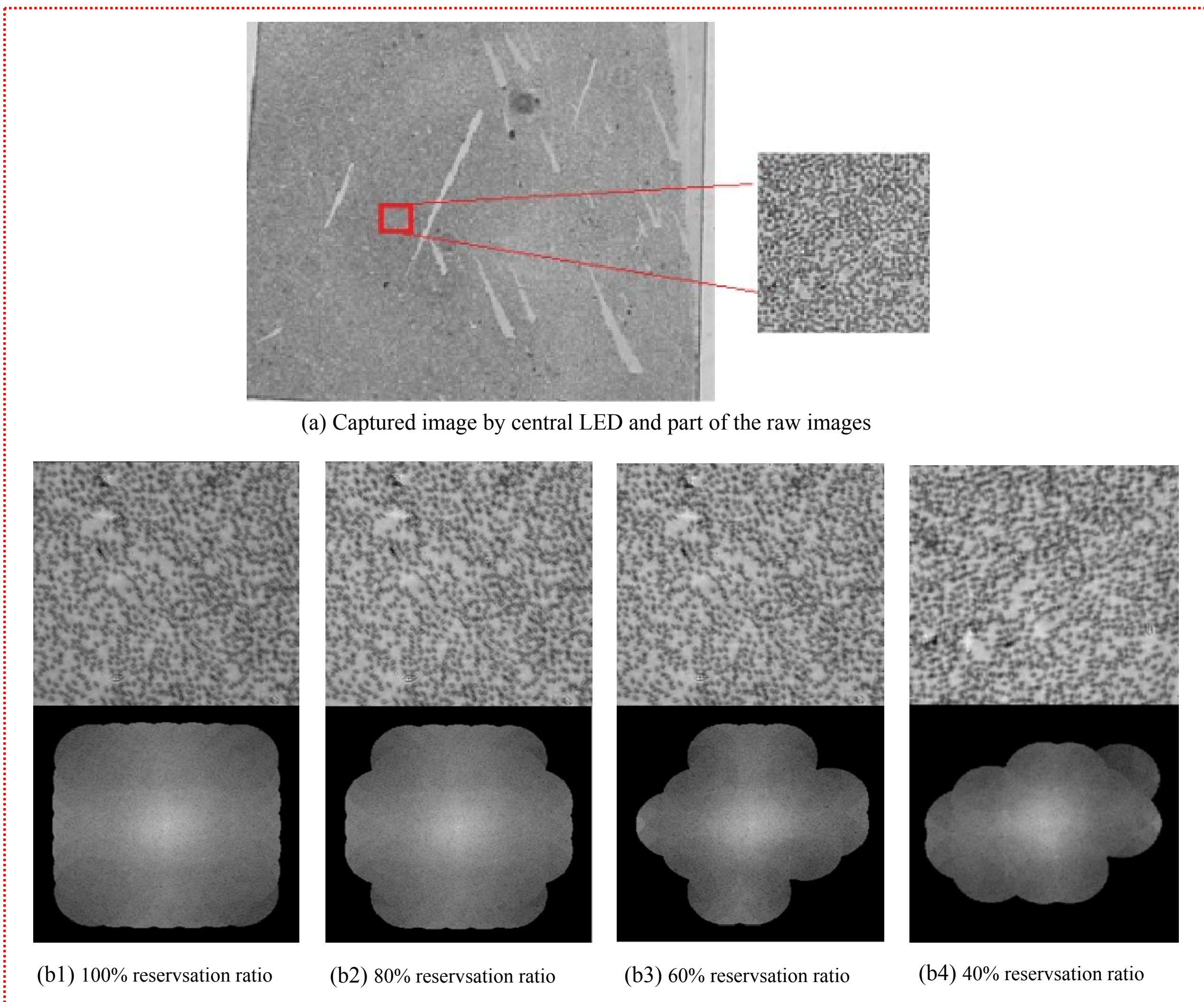

Figure. 2. Recovery of FPM with different reserved ratios of spectrum. (a) The raw image. (b1)-(b4) Recorved image and spectrum with different reserved ratios

In this paper, in order to get rid of the effect of iterations, they are set to 100. Comparing with Figure. 2(b2)-2(b4), the optimized fast spectral sampling FPM losses a part of high frequency information without decreasing the resolution of reconstruction rapidly. Actually, in the situation of 80% reservation ratio, the collection time can be decreased about 20%. Therefore, under the premise of not sacrificing the resolution (Figure. 2(b1) and Figure. 2(b2)), reducing captured images according to information content distribution in Fourier domain can decrease acquisition time.

Even though the AFP decreases reconstructing time, it also captures all measurements with 8×8 LEDs. So comparing with the AFP scheme, obviously, our scheme dividing the importance of the spatial spectrum before collecting images reduces acquisition time. Moreover, because all the calculations are in Fourier domain, the operating rate can increase.

4. CONCLUSIONS

In this paper, we have discussed the recent developments of FPM approach and verified the reliability of reserved ratio and restoration effect. In particular, we have also reported a new imaging process, which reduces the captured LR images and selectively updates the pixel values. By selecting the more important parts in Fourier domain, the optimized FPM can accelerate the conventional FPM processing. From the view of application, less acquisition time can be used for digital pathology cell screening and analysis.

We note that the accuracy of reconstruction is relative to the chosen samples' spectrum and different thresholds. Therefore, relatively, the selected scheme is coarse. According to the limitation, our on-going research is applying the concept of sparse coding sampling or forming multiple high dynamic range images into it, which may obtain a better reconstruction in all cases and may be well suited for imaging pathology slides.

ACKNOWLEDGMENTS

This work was supported by grants from Nation Science Foundation of China (No. 61172178, 61371132 and 61471043), and the International Science &Technology Cooperation Program of China (No. 2014DFR10960).

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