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RESOLUTION ENHANCEMENT USING FOURIER PTYCHOGRAPHY

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Abstract: Fourier Ptychography is a technique that is different from conventional microscopy used to construct a high-resolution image from several low-resolution images of the same scene. In this method, LED arrays replace the light source of a conventional microscope. LEDs are turned on in succession to take low-resolution images. As the position of the LED changes then the Fourier Transform of the image shifts. This method is better than conventional microscopy as there is moving parts and hence the results do not suffer from position accuracy. It helps to get an aberration-free large field of view of an image. In this paper, the imaging procedures in Fourier Ptychography are studied and the forward imaging model, recovery process, aberration correction, and sampling requirements are also discussed.

Keywords: Fourier Ptychography, resolution, conventional microscopy, diffraction pattern phase retrievel

1. Introduction

1.1 Ptychography:

It is based on periodic objects. Here, several diffraction patterns are recorded by changing the object's light so that only the overlap between surrounding diffraction orders occurs. Multiple diffraction patterns for non-periodic objects do not overlap equally with one another. Hence it is for periodic objects only. An outstanding approach came in picture which was converging very fast than other methods. This method is called ptychography iterative engine.

Ptychography iterative engine (PIE):

If object o(r) is scanned by illuminating probe given by probe function $P(r-R^j)$. Here R^j is the position of probe vector. Measured intensity pattern corresponds to each probe point. Success lies in the fact that probe positions overlap. The redundant information required for reconstruction is provided by this overlap. The captured intensity pattern for j^th^ probe position is given by:

$$I^j(u) = \Im\{O(r)P(r-R^j)\}$$

The position vectors in real space and reciprocal space, r and u respectively, are used here. J represents the quantity of scanned probe points.

To find the answer to $O(r)$ using the probe function $P(r)$ and the intensity patterns $I^j(r)$ for the appropriate probe point j.

The algorithm's steps are as follows if the estimated object for the k$^{\text{th}}$ iteration is $O_k(r)$:

- Calculate the exit wave field $\psi_k^j(r)$ as

$$\psi_k^j(r) = O_k(r)P\left(r - R^j\right)$$

- Take the Fourier transform of $\psi_k^j(r)$ to calculate the far field diffraction pattern :

$$\psi_k^j(u) = \Im\{\psi_k^j(r)\}$$

- Apply amplitude constraint

$$\psi_{c,k}^j(u) = \sqrt{I^j}(u)\ \frac{\psi_k^j(u)}{|\psi_k^j(u)|}$$

- Take the updated far field's inverse Fourier transform.

$$\psi_{c,k}^j(r) = \Im^{-1}\{\psi_{c,k}^j(u)\}$$

- Modify the part of the object that was illuminated by the probe and keep the rest same

$$O_{k+1}(r) = O_k(r) + a\frac{P * \left(r - R^j\right)}{P * |r - R^j|_{max}^2}\left(\psi_{c,k}^j(r) - \psi_k^j(r)\right).$$

  “a” is constant that define update step.

- Move to the next probe position.

1.2 Imaging procedures of Fourier Ptychography

In imaging systems one most important feature is space bandwidth product (SBP) [1]. It represents the content of the image transmitted through the system. It deals with total imaging area and smallest resolvable feature size. More SBP means more information and to increase this we can increase total imaging area which depends on lens size. Increasing lens size though increases SBP but at the cost of optical an aberration which is the feature of conventional lens system.to deal with this lensless imaging came in picture which does not show optical aberrations on increasing Numerical Aperture. Fourier Ptychography is a type of lensless imaging. So Fourier Ptychography deals with two most important problems [2-4]:

1. Phase retrieval [5-13]: We know that CCD’s or photographic plate’s measures only intensity variations of the image signal. Phase information which tells us about how much light is delayed during propagation is lost.so intensity only methods are used to recover this information.
2. Aperture synthesis [14-21]: it involves collecting multiple images from the telescope in Fourier domain and superimposes them to obtain high resolution.

The recovered image by this FP thus contains complete information.

1.3 Instrumentation:

A FP system consists of a platform having LED arrays as a source of light and a standard microscope that has a low numerical aperture and a large field of view but low resolution. The LED array emits light from multiple angles and at each angle the system records a low resolution image after passing through the lens. Now the constraint is imposed by the coherent transfer function. Thus the light incident on multiple angles of array and thus a high resolution image is obtained with large field of view and SBP.

2. Forward Imaging Model:

In this model image of the sample from multiple angles are captured. This process can be made as coherent imaging process as:

$$A_{output}(x,y) = h(x,y)\otimes(A_{object}(x,y)e^{ik_{xn}x+ik_{yn}y})$$

A_{object} = Complex amplitude of the object

$e^{ik_{xn}x+ik_{yn}y}$ = Incident plane wave with wave vector k_x, k_y

Transform the above equation to Fourier domain:

$$G_{output}\left(k_x,k_y\right) = H_{coh}\left(k_x,k_y\right)G_{object}(k_x - k_{xn}, k_y - k_{yn})$$

where, G_{object} = object spectrum in Fourier domain

Multiplying $e^{ik_{xn}x+ik_{yn}y}$ in spatial domain means shifting of object spectrum by amount(k_{xn}, k_{yn}) in Fourier domain. Also it is assumed that sample is in 2d. These assumptions allows the image to be mapped in Fourier domain.

Now the output image has only 64*64 pixels which is almost 4 time lower than the input image. Here only amplitude information is present and phase information is lost. Recovery of this phase is done by FP method.

3. Recovery Process:

Recovery process involves recovering phase of the image. It happens in following steps:

- The FP method makes a guess of high resolution object image in spatial domain,$\sqrt{I_h}e^{i\varphi_h}$ which is then transformed to Fourier domain.
- Now a small sub section of the image is selected and inverse Fourier transform is applied. This gives us a low resolution target image$\sqrt{I_l}e^{i\varphi_l}$.
- Replace the amplitude $\sqrt{I_l}$ with the square root of low resolution image obtained under different incident angle $\sqrt{I_{lm}}$ to form low resolution target image$\sqrt{I_{lm}}e^{i\varphi_l}$. Now Fourier transform is applied to this and again a small sub section is selected and then inverse Fourier transform is applied to it to update low resolution target image.
- Steps 2 and 3 are repeated for different incident angles. The corresponding sub regions obtained must overlap to get convergence. This process is repeated for all N images and thus high resolution image is obtained from low resolution mage.
- Steps 2, 3, 4 are carried out until the solution converges and is converted to spatial domain. Thus a final image is obtained having all phase information and high SBP as desired.

The final resolution of image from FP is dependent on the largest angle of light from LED matrix and not the NA.

4. Aberration Correction In FP:

In this section how aberrations are removed in FP is reviewed. Both known aberrations and unknown aberrations are removed in following sections.

4.1 Correcting Known Aberrations:

Known aberrations are made as pupil function in coherent imaging. The first coherent transfer function without aberrations is defined. Next, define a pupil function having to defocus aberration. Coherent transfer function with defocus aberrations is calculated. In forward FP then this aberrated coherent transfer function is used for low pass filtering and a low output image is obtained. In the recovery process invert the pupil function to remove the known aberration and iterations are carried out so that the final image has high SBP, wide field of view, high resolution, and is aberration-free [22].

4.2 Correcting Unknown Aberrations in FP:

Here two approaches for aberration correction are studied:

1. To use concepts of adaptive optics [23].
2. To recover both the high resolution complex object and the unknown abberated pupil function in multiple iterations [24].

4.2.1 First approach:

Here concepts of adaptive optics are used. A wave front sensor to measure the distortion and an adaptive optical element to correct the system.

Now to use this approach our need is to first define an image quality metric as a guide star and then perform the required corrections. Generally the sharpness metric use to calculate the gradient of the image.

Image quality metric:

Convergence Index: $\sum_{all\ incident\ angles} \frac{mean(\sqrt{I_l})}{\sum_{x,y} abs(\sqrt{I}_{lm-}\sqrt{I_l}}$

Where,

I_l = Low resolution target image

After defining convergence index correction using adaptive optics is evaluated.

4.2.2 Second Approach:

Here high resolution sample image and pupil function are recovered jointly in iterations called it as a EPRY (Embedded Pupil function Recovery) scheme.

5. Sampling Requirements Of FP:

In this section sampling requirement in spatial and Fourier domain is discussed. Sampling requirement in spatial domain:

For sampling two major questions need to address:

1. What will be the largest pixel size to get the low resolution image with fixed numerical aperture of the objective lens?
2. What will be the largest pixel size to get reconstructed image at fixed synthetic numerical aperture?

To answer the first question is: as FP is coherent imaging method and so its resolution is same as that of conventional imaging system. Resolution is given by λ/NA_{obj} and pixel size required is less than or equal to $\lambda/2NA_{obj}$ where 2 is due to Nyquist Theorem.

For second question is: the synthetic NA of the recovered image is the complex field image having amplitude and phase where intensity is used only. So to convert this complex to intensity by multiplying light field with its complex conjugate so that the phase information is lost and is given as E^*. This gives convolution in frequency domain. The passband of the reconstructed images doubles in frequency domain so the largest pixel size for reconstructed image will be given by$\lambda/4NA_{syn}$.

If largest pixel size is taken for both raw image and reconstructed image then the enhancement factor defined as:

$$\text{Enhancement Factor} = 2.NA_{syn}/NA_{obj}$$

A pixel size larger than $\lambda/2.NA_{obj}$ generally leads to aliasing in frequency domain. It will degrade the quality of reconstruction. To solve this problem the sub sampled scheme can be used [25].

Here one pixel is divided into 4 subpixels where the effective pixel size is only half of the original pixel size. Then a sub-sampled mask is created where the amplitude is updated. One sub-pixel is updated and three are remained unchanged in the amplitude redefining.

The aliasing cause problem in the sense that it does not leave enough bandwidth to use the circular pupil function in Fourier space and so final reconstructed images are corrupted.

The sub-sampled scheme is very useful and can be modified for other needs such as correcting the limited dynamic range of the detector in the process. Since image sensors have lower bit depth so multiple images with different exposure times for a LED are required.

6. Sampling Requirement In The Fourier Domain:

Success in FP reconstruction lies in the fact that data redundancy is required for the recovery process. A certain amount of overlap in the image spectrum is required between successive acquisitions in Fourier space.

The overlap is dependent on the illumination angle variation between two illuminations. In FP different illumination angles are provided by the LED matrix. More the overlapping percentage is better is the quality of the image. RMS error decreases if the overlapping percentage is increased. A minimum overlap percentage of 35% is required for a successful FP method.

One more important point that needs consideration is the translational symmetry of the sample. If the sample pattern has a periodic grid then some periodic artifacts would be introduced to the recovered pupil function and this is called raster grid pathology [8]. This would degrade the reconstruction quality. As the number of iterations increases, these artifacts would increase and decrease the reconstruction quality. However, for non-uniform sample patterns, periodic artefacts are not present in pupil function and the reconstruction converges at large iterations. So it is concluded that using a non-uniform sample pattern removes raster grid pathology

7. State Multiplexing In FP:

Let us assume that our light source is coherent that is single wavelength. For the incoherent light source, the light source has multiple wavelengths. This process is also called a mixed state decomposition framework [26-28].

It involves the following steps:

- Just like single wavelength, high resolution image is used and estimate intensity of the sample$\sqrt{I_h}e^{i\varphi_h}$.
- This sample is used to create many low resolution estimate of sample corresponding to different wavelengths.

- Intensity components of above obtained low resolution samples are added to obtain an incoherent mixture I_t.
- Now the ratio between the actual intensity I_m and I_t is used to update the corresponding intensity by multiplying this ratio to the actual intensity of each sample. Here the phase is remaining unchanged.
- These updated image samples are used to modify spectral regions.
- Now the previous steps are repeated for different angles until the solution converges.

In state multiplexed scheme the sample is illuminated by different colour LED with colours red, blue, and green at the same time. Now we get the incoherent mixture of the different coherent lights. Next in recovery process high resolution sample is obtained at different channels.

8. Imaging Modalities Of FP

Bright-field, phase and phase gradient imaging:

The FP reconstruction recovers both the intensity and phase of the sample. Once the phase information is recovered phase gradient images are generated which simulates the visibility of differential interference contrast. It is tough to recover information from the FP recovered intensity image, whereas this information can be gathered from the phase image [29].

To obtain the information from the phase profile illumination NA is greater than collective NA so that the dark field images are obtained which contain the information.

Dark field imaging:

In the bright field, we illuminate the sample from low angles and then move to large angles. The image is constructed in the Fourier domain and this image contains components of the pass band and high-frequency components as these contain most of the information required. So information from both the bright and dark field recoveries are obtained. A dark field has the advantage over a bright field in that it gives a high-resolution image with a great field of view. Similarly in reflective imaging and multi-scale imaging where the information is recovered in multiple layers along the optical axis.

9. Experimental Implementations And Imaging Modalities Of FP:

Experimental implementations of FP like the LED approach, LCD approach, and the aperture scanning approach is used. Various modalities using FP like a bright field, dark field, phase, reflective, phase gradient and multi-scaling imaging are discussed:

9.1 Experimental implementations:

9.1.1 LED array illumination:

We generally use an LED array in FP. In FP the incident angle of the LED rays should be larger than the collecting angle of the objective lens. Many dark field images are collected and also these images contain high-frequency information about the given sample.

In our FP prototype condenser lenses are replaced with the LED array. Each LED from the array illuminates the sample from a different angle. The images obtained from different illumination angles are then processed over multiple iterations to give a high-resolution image. In the experiment, for 2×0.8 N. An objective lens for acquiring the image and the final NA is 0.5. We have a large field of view due to a 2 × objective lens and high resolution due to the FP recovery process.

One important factor that needs to be considered for sample illumination is the sequencing in the frequency domain. So two factors are considered:

The first is the overlapping percentage in the domain and the second is the overlapping uniformity. For the LED array periodic grid is used and it incorporates two problems:

- Images for convergence required are very large with a high percentage of overlap.
- It also introduces raster grid pathology while reconstruction [30-31].

The solution to the above problem is that a non-uniform pattern is used in sampling using ring LEDs so that the aperture overlap percentage decreases from 50 % at the centers to 15 % at the edges. Also, this moves away from the linear symmetry so that it resolves raster grid pathology while reconstruction.so now fewer images are required in image processing.

Here largest incident angle determines the resolution. Lens aberration is corrected in the iterations. So now less number of low-quality images are required to obtain high-resolution images.

9.1.2 LCD array illumination:

Though using an LED array is cost-effective but it has some demerits as follows [32]:

- We need a plane wave by splitting the image into small tiles and LED does not give us plane waves.
- Intensity from the LED lights may fluctuate and this creates errors in the results.
- At the edge of the array the efficiency of delivering light is very low due to which high resolution image is not obtained.

One possible solution for this problem is to use the LCD for illumination. Various adjustments can be made to the LCD panel according to the requirements.

Advantages of using LCD:

- It is cost-effective and broadly compatible with compound microscopes.
- It provides a larger degree of freedom.
- The light illuminating from the condenser lens is plane wave as required.
- Here we have the option to set aperture to our requirement and so non-uniform sampling is done easily as compared to LED where their positions are changed.
- As we set patterns then the intensity do not fluctuate in this case.

Along with numerous advantages it has a disadvantage too. It has a low extinction ratio which can be increased by increasing the number of LCDs and arranging them in series.

10. Aperture Scanning FP For Holographic Imaging And Remote Sensing:

Plane waves are created by varied illumination angles for the sample. This had however a limitation that for this the sample must be thin. If the specimen is thin only then the low captured image by various angle illuminations is mapped in 2d Fourier domain. This allows the domain to impose the constraint and give the high-resolution image after certain iterations. If the sample is thick then the one-to-one mapping will not take place and support constraints cannot be applied [33]. Thus we will not get the required high-resolution image after certain iterations. Apart from the angle varying technique, there is another methodology that translates the aperture at the Fourier plane by illuminating one plane wave.

Here the key is to impose the aperture constraint at the Fourier plane.

The setup involves placing the object in the far field and moving the camera in an x-y plane to take images in various passbands. Thus the aperture acts as a support constraint in the Fourier domain.

Other implementations:
We can also do the process without lenses. Here object placed on the sensor is illuminated by angle varied plane waves. The recovery process toggles between the frequency domain and spatial domain where in the spatial domain intensity measurement is the constraint imposed and in the frequency domain, the CTF is used as the aperture constraint for the solution [34]. Once the complex field has been recovered at the detector, it is transferred to the object plane where a high-resolution image is obtained.

11. Discussion and Conclusion

The straightforward and adaptable Fourier ptychography approach has the potential to be used in many different research areas and businesses. One of the main features that differentiate it from other imaging techniques is its affordable capacity to reconstruct quantitative phase and gigapixel-scale images, but new and intriguing advantages keep appearing (e.g., 3D image capture, aberration removal, and novel compact optical arrangements, for example). In order to provide a fast comprehension of the working theory, its relationship to other techniques, and an overview of its most recent advancements and future prospects, this article described different features of FP.

The utilization of an LED array, which we employ to illuminate our microscope sample from a variety of angles, is a crucial aspect of our novel strategy. We take a different photograph every time a different LED is turned on. Each slanted LED's light efficiently directs fresh information coming from the sample into the microscope lens. There is enough data in the sequence of collected photos for us to computationally reconstruct very high resolution sample features (so far, down to approximately 300 nanometers). At the end of the day, we can roughly 50-100X increase the number of resolvable pixels in an image, producing some of the first gigapixel images in a motionless imaging system.

REFRENCES:

1. Lohmann A W, Dorsch R G, Mendlovic D, Zalevsky Z and Ferreira C, “Spacebandwidth product of optical signals and systems”, JOSA A 13 470–3 1996.
2. Zheng G, Horstmeyer R and Yang C., “Wide-field, high-resolution Fourier ptychographic microscopy”, Nat. Photonics 7 739–45 2013.
3. Zheng G, Ou X, Horstmeyer R, Chung J and Yang C 2014 Fourier Ptychographic Microscopy: A Gigapixel Superscope for Biomedicine Opt. and Photonics News 26–33 2014.
4. Zheng G, “Breakthroughs in Photonics: Fourier Ptychographic Imaging”, Photonics Journal, IEEE 6 1–7 2013.
5. Fienup J R, “Phase retrieval algorithms: a comparison”, Appl. Opt. 21 2758–69 1982.
6. Elser V., “Phase retrieval by iterated projections JOSA A 20 40–55 2003.
7. Faulkner H M L and Rodenburg J M., “Movable Aperture Lensless Transmission Microscopy: A Novel Phase Retrieval Algorithm”, Phys. Rev. Lett. 93 023903 2004.

8. Maiden A M and Rodenburg J M., "An improved ptychographical phase retrieval algorithm for diffractive imaging", Ultramicroscopy 109 1256–62 2009.
9. Gonsalves R., "Phase retrieval from modulus data" JOSA 66 961–4 1976.
10. Fienup J R., "Reconstruction of a complex-valued object from the modulus of its Fourier transform using a support constraint", JOSA A 4 118–23 1987.
11. Candes E J, Strohmer T and Voroninski V., "Phaselift: Exact and stable signal recovery from magnitude measurements via convex programming", Comm. Pure Appl. Math. 66 1241–74 2013.
12. Candes E J, Eldar Y C, Strohmer T and Voroninski V., "Phase retrieval via matrix completion SIAM Review 57 225–51 2015.
13. Waldspurger I, d'Aspremont A and Mallat S., "Phase recovery, maxcut and complex semidefinite programming", Math. Program. 149 47–81 2015.
14. Mico V, Zalevsky Z, García-Martínez P and García J., "Synthetic aperture superresolution with multiple off-axis holograms", JOSA A 23 3162–70 2006.
15. Di J, Zhao J, Jiang H, Zhang P, Fan Q and Sun W., "High resolution digital holographic microscopy with a wide field of view based on a synthetic aperture technique and use of linear CCD scanning", Appl. Opt. 47 5654–9 2008.
16. Hillman T R, Gutzler T, Alexandrov S A and Sampson D D., "High-resolution, widefield object reconstruction with synthetic aperture Fourier holographic optical microscopy", Opt. Exp. 17 7873–92 2009.
17. Granero L, Micó V, Zalevsky Z and García J., "Synthetic aperture superresolved microscopy in digital lensless Fourier holography by time and angular multiplexing of the object information", Appl. Opt. 49 845–57 2010.
18. Granero L, Micó V, Zalevsky Z and García J. "Synthetic aperture superresolved microscopy in digital lensless Fourier holography by time and angular multiplexing of the object information", Appl. Opt. 49 845–57 2010
19. Gutzler T, Hillman T R, Alexandrov S A and Sampson D D., "Coherent aperturesynthesis, wide-field, high-resolution holographic microscopy of biological tissue", Opt. Lett. 35 1136–8 2010.
20. Meinel A, "Aperture synthesis using independent telescopes", Appl. Opt. 9 2501 1970.
21. Turpin T, Gesell L, Lapides J and Price C., "Theory of the synthetic aperture microscope", Proc. SPIE 2566 230–40 1995.
22. Ou X, Zheng G and Yang C., "Embedded pupil function recovery for Fourier ptychographic microscopy", Opt. Exp. 22 4960–72 2014.
23. Bian Z, Dong S and Zheng G., "Adaptive system correction for robust Fourier ptychographic imaging", Opt. Exp. 21 32400–10 2013.
24. Dong S, Bian Z, Shiradkar R and Zheng G., "Sparsely sampled Fourier Ptychography", Opt. Exp. 22 5455–64 2014.
25. Dong S, Shiradkar R, Nanda P and Zheng G., "Spectral multiplexing and coherent-state decomposition in Fourier ptychographic imaging Biomedical", Opt. Exp. 5 1757–67 2014.
26. Thibault P and Menzel A, "Reconstructing state mixtures from diffraction measurements", Nature 494 68–71 2013.

27. Batey D J, Claus D and Rodenburg J M. “Information multiplexing in Ptychography”, Ultramicroscopy 138 13–21 2014
28. Zheng G, Horstmeyer R and Yang C., “Wide-field, high-resolution Fourier ptychographic microscopy”, Nature Photonics 7 739–45 2013.
29. Guo K, Dong S and Zheng G., “Fourier Ptychography for Brightfield, Phase, Darkfield, Reflective, Multi-slice, and Fluorescence Imaging”, IEEE J. Select. Topics Quant. Electr. at press 2016.
30. Thibault P, Dierolf M, Bunk O, Menzel A and Pfeiffer F., “Probe retrieval in ptychographic coherent diffractive imaging”, Ultramicroscopy 109 338–43 2009.
31. Guo K, Dong S, Nanda P and Zheng G., “Optimization of sampling pattern and the design of Fourier ptychographic illuminator”, Opt. Exp. 23 6171–80 2015.
32. Guo K, Bian Z, Dong S, Nanda P, Wang Y M and Zheng G., “Microscopy illumination engineering using a low-cost liquid crystal display”, Biomed. Opt. Exp. 6 2015.
33. Dong S, Horstmeyer R, Shiradkar R, Guo K, Ou X and Bian Z., “Aperture-scanning Fourier ptychography for 3D refocusing and super-resolution macroscopic imaging Opt. Exp. 22 13586–99 2014.
34. Ou X, Horstmeyer R, Yang C and Zheng G., “Quantitative phase imaging via Fourier ptychographic microscopy”, Opt. Lett. 38 4845–8 2013.