Retrieval of non-sparse objects through scattering media beyond the memory effect

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Abstract
Optical imaging through scattering media is commonly constrained to sparse objects and the optical memory effect. To solve the problems, a method based on the combination of ptychography and the shower-curtain effect is presented here to achieve the retrieval of non-sparse samples through scattering media beyond the memory effect. The phase disturbance introduced by scattering media can be neglected based on the shower-curtain effect, and also the field-of-view can be extended via the ptychography. Results of the retrieval of hair-follicle cell from human skin demonstrate the effectiveness and feasibility of the proposed method for static and dynamic scattering media with the extended field-of-view to be 3.2 mm × 3.2 mm. The present work may be an approach for imaging through deep biological tissues.

Keywords: scattering medium, Image reconstruction, shower-curtain effect

(Some figures may appear in colour only in the online journal)

1. Introduction

When a light beam propagates through scattering media, such as fog, haze, and biological tissues, it is scrambled into a highly disordered speckle pattern because of the multiple scattering inside the media, preventing the image formation of optical systems. Consequently, imaging through scattering media is a challenge that must be overcome for applications in such fields as astronomical observation, biomedical imaging, and so on. To compensate wavefront aberration from atmospheric scattering and turbulence, adaptive optics [1] has been exploited to improve imaging reconstruction in astronomical telescopes. However, the compensation ability of the adaptive optics is limited by the accuracy of wavefront detectors. In the past decade, the wavefront-shaping technique was proposed and further developed for focusing or imaging through scattering media. The wavefront distortions can be compensated by using spatial light modulators (SLM) with various approaches, e.g. iterative optimization [2–5], optical phase conjugation [6–9], and transmission matrix measurement (TM) [10–13] to search the appropriate correction phase. Nevertheless, the requirement of a guide star and the low efficiency of feedback control mechanism restrict the speed and efficiency of focusing and imaging. In recent years, speckle correlation imaging methods [14–19] were proposed to reconstruct objects hidden behind scattering media, benefitting from the correlation characteristics of speckle pattern within the region of optical memory effect of scattering media. The so-called optical memory effect refers to the spatial translation-invariance of the speckle pattern when a point source of the object shifts within a certain range through the scattering medium. The memory effect commonly occurs in an immobilized turbid medium within a limited range of field-of-view (FOV), which is determined by the effective thickness of the scattering medium. The iterative phase retrieval algorithm employed in the speckle correlation imaging method has low reconstruction efficiency due to the randomly assigned initial values and the low accuracy of phase retrieval caused by local minimum convergence [15].
In addition, Katz et al demonstrate that the contrast of the speckle pattern reduces with increasing of object’s sparsity, resulting in inaccurate image reconstruction for speckle correlation imaging method. Consequently, the method generally performs better for sparse objects, consisting of a small number of nonzero elements such as a binary object, separately tagged point-like object, and so on. Ptychography is a computational imaging method to obtain the image of the object by processing a set of diffraction patterns of the object with the ptychographic iterative engine (PIE) algorithm [20, 21]. This method is not restricted by the non-sparse object and can obtain a larger FOV by scanning an aperture in the front of the object plane. However, when the object is hidden behind the scattering medium, it fails to record the diffraction patterns, resulting in the failure of the image reconstruction.

To address these issues, in this paper, we propose a method for reconstructing hidden objects behind scattering media by using the ptychographic method incorporated with the shower-curtain effect. The shower-curtain effect [22, 23] means that the intensity distribution in the front surface of the scattering medium is equal to the back surface. So, if the pattern at the back surface of the scattering medium is recorded by the camera, the intensity distribution in the front surface, as well as diffraction pattern of the object will be known.

By scanning an aperture placed close to the object in two dimensions, a set of patterns are collected. With the extended PIE algorithm employed to the ptychography, the non-sparse object is reconstructed with a large FOV beyond the memory effect range. The experimental results verified the effectiveness and feasibility of the proposed method for reconstructing objects through both static and dynamic scattering media.

2. Methods

Figure 1(a) shows the experimental setup for imaging through the scattering medium via a combination of the ptychography and the shower-curtain effect. A continuous wave (CW) laser with wavelength of $\lambda = 532$ nm is used as an illumination source. After expanded and collimated, the beam illuminates an aperture with the diameter of 2 mm, which is mounted on a xy stage with a step precision of 10 $\mu$m. To employ the shower-curtain effect, we image the surface of the scattering medium (DG10-220, Thorlabs, USA) onto the sensor of CCD camera (Neo 5.5, Andor Inc., UK) with 2560 $\times$ 2160 pixels and pixels size 6.5 $\mu$m $\times$ 6.5 $\mu$m, by using a 4-f optical imaging configuration ($L_1$ and $L_2$). In this case, if the object is close to the scattering medium, it can be imaged directly on the camera (as shown in figure 1(b)). In practical case, the object is placed away from the scattering medium, so there is a transmission distance from the object to the scattering medium. Thus, the light distribution in the front surface of the scattering medium is the diffraction pattern of the object, which is captured by the camera (as shown in figure 1(c)).

Owing to the shower-curtain effect, the random phase disturbance of the scattering medium is ignored. To reconstruct the object from the diffraction distribution, the ptychography is employed. By scanning the aperture along $x$ and $y$ directions, the light passing through the aperture illuminates different parts of the object, and a series of diffraction patterns, $I_1, I_2 \ldots I_m$, are generated and recorded.

The object is reconstructed by superimposing these intensity patterns with the following algorithm, whose flow chart is shown in figure 2. The initial object $O_0(x, y)$ and probe wavefront $P_0(x, y)$ are assumed as identity matrix. The exit wavefront at the object plane respect to the $m^{th}$ aperture position is described by:

$$E_m(x, y) = O_m(x, y) \cdot P_m(x, y).$$  

The light field $E_m(x, y)$ propagates to the scattering medium plane, whose wavefront $E_m(x_s, y_s)$ can be calculated by the angular spectrum (AS) transform [24]:

$$E_m(x, y) = C \int \int U_m(f_x, f_y) e^{i(2\pi f_x x + 2\pi f_y y + \lambda f_x^2 + \lambda f_y^2 + \phi)} e^{-i2\pi(f_x x + f_y y)} \, df_x \, df_y$$  

in which:

$$U_m(f_x, f_y) = \mathcal{F} \{E_m(x, y)\}.$$  

Here $\mathcal{F}(\cdot)$ represents the Fourier transform; $x$, $y$ and $x_s$, $y_s$ refer to spatial coordinates in the object plane and the scattering medium plane; $C$ is a constant; $f_x$, $f_y$ is the spatial frequency; $d$ is the object-to-scattering medium distance.

Owing to the shower-curtain effect, the intensity pattern in the front surface of the scattering medium is directly imaged onto the camera and recorded as $I_m(x_s, y_s)$. The modulus of the wave field in the surface of scattering medium is then replaced by the square root of the $I_m(x_s, y_s)$, and the new light field becomes:

$$E'_m(x_s, y_s) = \sqrt{I_m(x_s, y_s)} e^{i\alpha_m(x_s, y_s)}.$$  

An updated wavefront $E'_m(x, y)$ in the object plane is then calculated from $E'_m(x_s, y_s)$ via the inverse angular spectrum (AS$^{-1}$) transform. By updating the current object $O_m(x, y)$ and probe wavefront $P_m(x, y)$, we can generate the new object $O_{m+1}(x, y)$ and probe $P_{m+1}(x, y)$. The updated functions are given by:

$$O_{m+1}(x, y) = O_m(x, y) + \alpha \frac{P_m^2(x, y)}{|P_m(x, y)|^2_{\text{max}}} \cdot (E_m^2(x, y) - E_m(x, y))$$  

$$P_{m+1}(x, y) = P_m(x, y) + \beta \frac{O_m^2(x, y)}{|O_m(x, y)|^2_{\text{max}}} \cdot (E_m^2(x, y) - E_m(x, y))$$  

where the parameters $\alpha$ and $\beta$ are usually set as 1 [25].
Figure 1. Experimental setup for imaging through the scattering medium. (a) Schematic of imaging via the combination of ptychography and shower-curtain effect. (b) Schematic of an object closely attached to the scattering medium. (c) Schematic of an object away from the scattering medium.

Figure 2. The whole procedure of the reconstruction algorithm. AS represents the angular spectrum transform; AS\(^{-1}\) denotes inverse AS; SSE represents the sum-square error between the calculated amplitude and the square root of recorded intensity; \(m\) and \(M\) represent the number and the total numbers of recorded patterns; \(\varepsilon\) is the preset criterion value.

The process continues until all the recorded \(M\) patterns are employed to update the object and probe wavefront to complete a single iteration. To quantify the accuracy and convergence of the algorithm, the sum-squared error (SSE) is employed after each iteration, which is defined as:

\[
SSE = \frac{\sum_{m=1}^{M} \left| A_m(x, y) - \sqrt{I_m(x, y)} \right|^2}{\sum_{m=1}^{M} I_m(x, y)}
\]

where \(A_m(x, y)\) indicates the calculated amplitude distribution. The criterion value \(\varepsilon\) is preset. If \(SSE < \varepsilon\) satisfies, the iteration ends, and then outputs the reconstructed object \(O_{m+1}(x, y)\) and the probe \(P_{m+1}(x, y)\). Otherwise, it will start the next iteration from the first recorded pattern.

3. Results and discussion

To verify the effectiveness and feasibility of the proposed method, experiments have been carried out. The object is located at a distance of 50 mm away from the scattering medium. The radius of the aperture is \(r = 1\) mm. After each pattern is captured, the aperture is shifted to adjacent position, making sure an overlapping area between them. The shift of the aperture continues by moving the stage along \(x\) and \(y\) directions, resulting in a total of 25 patterns recorded in a grid of \(5 \times 5\) aperture positions with step length of \(s = 0.3\) mm (figure 3(b)). The redundant data from overlapping area is introduced into the collected data and allows retrieval of the complex amplitude field. As reported \[26, 27\], an overlap rate of around 75%–85% is required for high-quality reconstruction. According to geometrical optics, the overlapping area \(S\) can be calculated by:

\[
S = \frac{\arccos\left(\frac{s}{r}\right)}{90} \cdot \pi r^2 - s\sqrt{r^2 - \frac{s^2}{4}}.
\]

Thus, the overlap rate \(R\) between adjacent illumination areas is given by:

\[
R = \frac{S}{\pi r^2}
\]

which is equal to the value of 81% in the experiment.

The recorded patterns of a USAF resolution chart are shown in figure 3(a). To reduce computation time, only non-zero useful information with \(508 \times 508\) pixels of each pattern is employed in the reconstruction process. In the iteration, the criterion value \(\varepsilon\) is set to be 0.01. After 50 iterations, the reconstructed object is shown in figure 3(d). In the experiment, the effective thickness of the scattering medium (DG10-220, Thorlabs, USA) is 8.5 \(\mu\)m, resulting in the region of memory effect within \(0.9 \times 0.9\) mm\(^2\). Therefore, the maximum FOV is \(0.9 \times 0.9\) mm\(^2\) for imaging through the scattering medium based on the memory effect. In the proposed method, the FOV is determined by the covered area of the aperture, as is shown in figure 3(b). It is calculated to be \(3.2 \times 3.2\) mm\(^2\), which
Figure 3. The experimental result for imaging a resolution target through the scattering medium. (a) The central parts of recorded patterns. (b) Overlapping aperture. (c) Scanning path of the aperture. (d) Reconstructed object. \( r \) and \( s \) represent the radius of the aperture and the step size, respectively; STD: standard deviation.

Figure 4. The experimental result for imaging the hair-follicle cell of human skin through the scattering medium. (a) The central parts of recorded patterns. (b) The used object for imaging. (c) The reconstructed object hidden behind the scattering medium.

is extended beyond the memory effect range. The FOV can be further enlarged by scanning the aperture extensively with more positions to record more patterns of the object.

To exploit the performance of the proposed method for imaging non-sparse biological samples, the object is replaced with a paraffin slice of hair-follicle cell of human skin. Figure 4(a) presents some sub-images with the size of 508 × 508 pixels. The reconstructed object is shown in figure 4(c). By comparing the object (figure 4(b)) and the reconstruction (figure 4(c)), we can see an effective reconstruction for those structures marked by dashed rectangles. On the contrary, the speckle correlation method restricted in sparse objects cannot reconstruct such biological samples [15, 18, 19]. Thus, the proposed method dismisses the requirement of sparse objects and provides an approach for biological imaging through scattering media.
Another key feature of the shower-curtain effect is that the phase aberration introduced by scattering media will not influence the intensity distribution on the detector. Thus, the scattering medium can be viewed as a screen on which images of ptychography are projected. Consequently, the scattering medium is not required to be static during the imaging process. To verify this advantage, we employ the same scattering medium mounted on a motor to rotate it (50 revs s$^{-1}$) to simulate the dynamic scattering medium. A total of 25 speckle patterns in accordance with the static way are recorded. As expected, we accurately reconstruct the objects, as shown in figures 5(b) and (c). Interestingly, the quality of retrieved images through the dynamic scattering medium is better than that through the static medium. To compare the background noise level in static and dynamic cases, the standard deviations (STD) of the given areas marked with white rectangles in figures 3(d) and 5(b), are calculated as quantitative indicators. The low value of STD corresponds to a low background noise level. In the static case, the STD is 0.39, while it is 0.22 in the dynamic case. The reason is that the speckle noise introduced by the scattering medium is averaged out by rotating rapidly. Thus, the quality of the reconstructed images is improved.

To further demonstrate the feasibility of the proposed method for imaging through biological tissues, the scattering medium is replaced with an onion skin tissue (figure 6(a)) to repeat the above experiment. The hidden objects are retrieved as well with high fidelity, as seen in figures 6(b) and (c). Therefore, we can conclude that the dynamic property of scattering media can improve the reconstruction quality of the object.

4. Conclusion

In summary, we have proposed a method for imaging non-sparse objects through scattering medium with a large field-of-view by the combination of ptychography and shower-curtain effect. With the help of ptychography, the non-sparse object can be reconstructed. The field-of-view is extended beyond the range of the memory effect, and further enlarged by scanning the aperture extensively to record more patterns. The property of the shower-curtain effect makes the method insensitive to dynamic turbid media. Thus, the dynamic scattering medium is more suitable for image reconstruction in this case. These advantages provide a potential approach for practical biomedical applications such as imaging through scattering brain tissues. The intrinsic dynamic property of living biological tissues has been a major challenging factor in most exiting methods. In contrast, this feature is no longer an impediment but instead a key enabling factor in our method. In addition to the application in imaging through deep biological tissues, the proposed method may also find applications in such fields as astronomical observation for imaging the object through the turbulent atmosphere, and so on.
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