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Multiplexing and de-multiplexing with scattering media for large field of view and multispectral imaging

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ABSTRACT

Large field of view multispectral imaging through scattering medium is a fundamental quest in optics community. It has gained special attention from researchers in recent years for its wide range of potential applications. However, the main bottlenecks of the current imaging systems are the requirements on specific illumination, poor image quality and limited field of view. In this work, we demonstrated a single-shot high-resolution colour-imaging through scattering media using a monochromatic camera. This novel imaging technique is enabled by the spatial, spectral decorrelation property and the optical memory effect of the scattering media. Moreover the use of deconvolution image processing further annihilate above-mentioned drawbacks arise due iterative refocusing, scanning or phase retrieval procedures.

Keywords: scattering media; speckle imaging; memory effect; single-shot imaging; lensless imaging; multispectral imaging; large field of view imaging; deconvolution

1. INTRODUCTION

Visual information is the essential ingredient in all aspects of life, and optical imaging has been the primary mode of collecting information. The light propagation mediums provided by the nature are not always close to the ideal free space, which causes visual deformation from the view point of human eyes (or camera). The light passing through these scattering medium produces random speckle patterns,¹ and appears as additive noise in the images. The examples of the scattering in optical imaging are ranging from astronomical observations through atmosphere² to microscopic imaging of the biological tissues.³ When the medium become increasingly turbid, we could only be able to perceive the speckles with no visual information of the underlying object. Until recent years, these speckle patterns were treated as noise covering the object of interest in background. In fact, these speckles carry ample information about the object, but they are scattered.

Looking through scattering media has many applications ranging from imaging through skin for biomedical applications or in surveillance in foggy days. In recent years, quite a good amount of progression has been made in this field due to advancement of electronics and signal processing techniques. The phase conjugation, scattering-matrix inversion, ultrasonic encoding are the example of such techniques for high resolution imaging and focusing behind scattering medium. In all these techniques, the ability to image through scattering media is mostly facilitated by characterizing the scattering medium. For example, using a guide-star in the object plane, and iteratively correcting the aberrations induced by the medium;⁴ or recording the scattered field and reversing to focus the light back onto the object plane.⁵ The speckle correlation or the memory effect (ME) of the scattering medium is another such technique, which has been the main catalyst to the field. The work presented here is in alignment with this technique.

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The memory-effect is a peculiar phenomenon observed when light propagates through a scattering medium, which was first highlighted in the 1980s.^{6,7} The seemingly-random speckle patterns observed after the scattering medium are highly correlated for a certain range of incident angles, which is known as the angular memory-effect range. Deconvolution is a well-known technique in signal/image processing from 1970s,⁸ which has been widely used in astronomy,⁹ microscopy,¹⁰ as well as non-optical imaging.¹¹ It relies on the linear shift invariant property of imaging systems for which the deformed image recorded by an instrument can be written as the convolution of the perfect object function with the point spread function (PSF), i.e. the optical systems response to a point source. By having the knowledge of PSF of the system, one can restore a high quality image from the measured one using deconvolution.¹² It is even known to yield better resolution than the diffraction limit and improves image contrast.¹³

The power of the deconvolution operation has been known for decades and being used to correct for aberrations in optical systems. However, it had not been exploited for imaging through scattering media until recently. The correlation properties of the memory effect implies a spatially-invariant PSF within the memory-effect angular range. Thus, within the memory-effect range, deconvolution microscopy can effectively be used for high-quality image reconstruction through the scattering layer. Some recent studies using deconvolution processing has shown promising results on image reconstruction from the speckle patterns.^{14,15} However, one of the inherent benefits of using deconvolution has not been explored yet, i.e. deconvolution allows us to multiplex multiple decorrelating PSFs, and enables us to obtain high speed, high resolution, and high dynamic range colour imaging using dense monochromatic CCD matrix. Here, using the spectral decorrelation property of the scattering media, and spatially-invariant property of the PSF (i.e. the memory effect), we have first successfully demonstrated a color image recovery from the monochromatic image of a composite colored object. Then by utilizing the decorrelation of PSFs from the point out of memory effect range, we demonstrate the large field of view imaging by de-multiplexing these multiple PSFs from a single shot image.

Figure 1. Experimental setup and reconstructed colourful object through a scattering medium from a monochromatic CCD. (a) Experimental setup: a common projector, two irises and monochromatic CCD. (b) 3-spectral-band NTU letters on the projector. (c) The raw CCD image (grey scale) with 512×512 pixels. (d) Reconstructed colourful image.

2. PRINCIPLE

Unlike PSF of the lens system, the PSF of a strongly scattering medium is a random speckle pattern. We assume the linear shift-invariant property of the *PSF* in the scattering media. This assumption is valid as long as we are operating within the memory effect region of the scattering medium.¹⁶ The captured image *I* is the convolution (denoted as $*$) of an object *O* with the optical system PSF, which can be expressed as:

$$I(x, y) = \sum_{(i, j)} O(i, j) PSF_{ij}(x - i, y - j) \quad (1)$$

In the era of computational imaging, the object can be exactly recovered from the image I , if we are aware of the PSF of the optical system; this is known as deconvolution. The deconvolution process can ideally be expressed as follows.

$$O = deconv(I, PSF) = FFT^{-1} \left(\frac{FFT(I)FFT(PSF)^c}{|FFT(PSF)|^2} \right) \quad (2)$$

where $(.)^c$ is the complex conjugate, $FFT(.)$ and $FFT^{-1}(.)$ are the Fourier transform and its inverse, respectively. The deconvolution is possible because the convolution in spatial domain become the multiplication in Fourier domain.

$$FFT(O * PSF) = FFT(O)FFT(PSF) \quad (3)$$

Interestingly, the PSF of strongly scattering media, i.e. the randomly distributed speckle pattern, is strongly dependent on wavelength. It means the measured image I is a composite response of scattering media with all the wavelengths in the light spectral bandwidth.

$$I = \sum_{\lambda} I_{\lambda} = \sum_{\lambda} O_{\lambda} * PSF_{\lambda}, \quad (4)$$

Its known from the speckle phenomenon that each distinct band of light produces uncorrelated speckle if they are spectrally separated enough. In an ideal case, this can be mathematically expressed as follows. P

$$PSF_{\lambda_1} \star PSF_{\lambda_2} = \begin{cases} 0 & \text{if } \lambda_1 \neq \lambda_2 \\ \delta & \text{if } \lambda_1 = \lambda_2 \end{cases} \quad (5)$$

where $\star$ is the correlation operator, and δ is the spatial impulse function. The actual uncorrelated values reduce to an insignificant value in finite dimension, which we have expressed as 0 for simplicity. As a result of this interesting phenomenon, the following relationships can be deduced.

$$FFT(I)FFT(PSF_{\lambda})^c = FFT(I_{\lambda})FFT(PSF_{\lambda})^c$$

It is because of $FFT(A \star B) = FFT(A)FFT(B)^c$, and the correlation of PSFs from different wavelengths reduced to insignificant values. Therefore each spectral component of the object can be reconstructed from a single monochromatic image I as follow.

$$O_{\lambda} = deconv(I, PSF_{\lambda})$$

A more detailed view of these techniques can be found in.^{17, 18} An interesting application of the aforementioned technique in text encryption can be found in.¹⁹ In essence, we are trying to convey that each spectral PSF can do the job of image reconstruction as well as the spectral filtering from the measured broadband speckle intensity. It is worth to note that the single wavelength presented in these equations can be extended to be a limited spectral band or can be even other parameter as long as the equation (5) is true.

3. EXPERIMENT

The schematic of the optical experimental setup and a reconstructed multispectral (or colourful) NTU object through the scattering medium from a monochromatic camera are presented in the Figure 1. A common projector is used for displaying various desired objects with 3 different spectral bands which are corresponding to 3 colors of red, green and blue in display technology (Fig. 1b). The light coming from the colourful objects passed through the diffuser (i.e. the strongly scattering media) and generate the scattering diffraction pattern on a high-dynamic monochromatic CCD as presented in Fig. 1c. We use a single pixel at the center of projector to measure 4 PSFs corresponding to 4 different spectral bands: red, green, blue and white. The white pixel is essentially the sum of red, green and blue bands in the projector display technology. Then by applying standard deconvolution algorithm, we could reconstruct a high fidelity, multispectral object (Fig. 1d).

For the first step of the reconstruction, we verify spatially shift-invariant region of PSF for the widest spectrum, i.e. the white light. One white pixel moves linearly by the projector and corresponding PSFs are measured

Figure 2. Correlation coefficient of variant speckle patterns when moving the central white pixel from $-660 \mu\text{m}$ to $660 \mu\text{m}$ with a step of $220 \mu\text{m}$. The top colourful NTU presents a multispectral object in the position of experimental region in Figure 1. The insets indicate nearly spatially-invariant speckle patterns with 56×56 pixels regions.

Figure 3. Variant PSFs and corresponding reconstruction images. (a-d) Speckle patterns for variant colours of the central pixel, equivalent to white, red, green and blue PSFs. (e-h) Reconstructed images with variant PSFs.

at each position. In Figure 2, we calculate the cross coefficients of variant speckle images (or PSFs) with respect to the center one. The insets show partially correlated speckle images with different locations of white pixels on projector, corresponding to the position from $-600 \mu\text{m}$ to $600 \mu\text{m}$ with a step of $220 \mu\text{m}$. Also, at the top of Figure 2, we display the colourful NTU letters in our experiments to confirm we could obtain a highly correlated PSF in the operating region for reconstruction. We show here the variant white PSFs as the reference to confirm almost spatially shift-invariant region for the widest spectral band, while narrower spectrum illumination extends the shift-invariant region and increases higher contrast of speckle images. It is the reason that in the previous experiments,¹⁶ the super narrow bandwidth pseudo-incoherent source of a laser with a rotating diffuser (or a strong white light source with a narrow band filter) was preferable. The four PSFs corresponding to 4 spectral bands of white, red, green and blue are shown in the Fig. 3(a-d), respectively. Figure 3(e-h) show the corresponding reconstructed images with 4 spectral PSFs (a-d) from a single monochrome speckle image (Fig. 1c). The results present the spectral filter function of our spectral PSFs.

Figure 4. Limited FOVs with various spatial PSFs. (a-d) A group of successful reconstructions of the object. Scale bars: $1000\mu\text{m}$.

Figure 5. Superposed reconstruction to enlarge the limited reconstruction area. Various reconstructions are stitched together to extend the limited reconstruction area. Scale bars: $1000\mu\text{m}$. Dashed red circles indicate the limited FOV of the central PSF. Solid red circle indicates the enlarged FOV.

3.1 Enlarging Filed of View

The multiplexing and demultiplexing techniques presented in equation (4) and (5) can be extended to imaging of multiple regions of interest. It is because the scattering media produced uncorrelated speckle patterns beyond the ME region. Thus we can simply interpret these spectrum dependent PSFs (PSF_λ) in terms of region dependent PSFs. In this work, we explore more information from the non-paraxial region and find an alternative way to extend the FOV while imaging with a strongly scattering medium using a single shot. We present various spatial point sources on the object plane and measure the corresponding PSFs, then utilize a single speckle image to execute deconvolution process. Fig. 4 shows four typical reconstructions with four different spatial PSFs. We need note that the PSFs and available reconstruction regions (ME range) on image plane are unique and different for different spatial positions due to the random nature of the scattering medium. Therefore one could observe

the different reconstruction FOV, for example, the FOV in Fig. 4c seems larger than that in Fig. 4a.

We have demonstrated our principle to demultiplexing the spatial information multiplexed into one single speckle image through various spatial PSFs in Fig. 4. However, for each individual reconstructed image, the information of interest are shifted to the center, and it is necessary to arrange them to form a single image with an enlarge FOV. We need to shift the reconstructed images according to the region associated with the PSFs, whose positions are predetermined. In fact, PSFs could record the shift of the speckle patterns and one could confirm their position through calculating the cross-correlation coefficient (even though the value maybe very low) to arrange the regional reconstructed images. If the regional PSF is measured for the point at position (ux, uy) , the recovered region on image plane should be centered at position (vx, vy) , where v/u is the magnification. Now we can superpose these reconstructed regions to form the enlarge FOV as shown in Fig. 5.

Figure 6. Multispectral imaging of fluorescent samples (QD sample). (a) Tilted light beam from a blue laser focus on a NTU sample with two labelling QDs. (b) Fluorescent spectra from two QDs. (c) Measured speckle pattern on the camera from colorful NTU sample and the corresponding PSFs as two pinholes respectively labeled these QDs are placed at the object plane. (d) Reconstructed spectral images with red and green PSF, a composite multispectral image reconstructed by our technique and a fluorescent microscopy image as reference, respectively. Scale bars: 1000 μm in (c) and 100 μm in (d).

3.2 Multicolour Imaging

To showcase a practical application we have performed multispectral imaging of a fluorescent sample. The complete experimental setup for a real object decorated with multi-colour fluorescent materials, i.e. colloidal quantum dots (QDs), and experimental data are schematically presented in Fig. 6. The object is lithography mask on glass with opening of 3 letters NTU on which two different quantum dots are decorated. The quantum dots are well known fluorescent materials with super narrow emission band width and colour tunability used in biology labeling or optoelectronic devices.^{20–22} In this experiment, we choose red and green QDs with spectra presented in Fig. 6(b) which shows two quantum dots radiate good red and green light without spectral overlap. A tilted light beam from a blue laser (CPS450, wavelength: 450nm) focus into QDs. After propagating through a long-pass edge filter (BLP01-473R-25), a diffuser (Edmund, 120 Grit Ground Glass Diffuser) and an iris, a mixed spectral scattering pattern is recorded on the monochromatic camera (Andor Neo 5.5, 2560×2160, pixel size 6.5 μm). The distances of u and v are about 240 mm and 65 mm respectively, then the magnification between the image and object plane is about 0.27. For the green and red PSF measurements, two pinholes with diameter

about 90 μm emitting red and green colours from two QDs are presented at the object plane and corresponding speckle patterns as the spectral PSFs are captured on the camera and recorded for the post-processing algorithm. Then a colorful NTU sample with size of about 1.47mm $\times$ 0.38mm is placed at the position of the pinholes and acted as a real colorful object, as the inset presented in Fig. 6(a). Figure 6(d) shows the recovered spectral image by deconvolving the speckle pattern with corresponding spectral PSFs in Fig. 6(c). Each spectral PSF successfully reconstructs the correct spectral part of object. A composition of these two individual red and green patterns is also presented as a good spectral reconstruction in comparison with the fluorescent microscopy image.

4. CONCLUSION

We have demonstrated an enlarged field of view and multiple spectra for imaging through scattering media by utilizing multiple memory effect regions, and its spectral demultiplexing ability. A single-shot speckle pattern contains essential spatial and spectral information of the object, the information is multiplexed randomly within the FOV of the imager. The deconvolution algorithm utilises the shift invariance (i.e. spatial correlation) of the PSFs for image reconstruction, while the orthogonality between the regional PSFs (i.e. spatial decorrelation) and orthogonality between spectral PSFs makes them play the role of spatial and spectral segregation. Any object region of interest can be retrieved by using the corresponding PSF of that region. Similarly, any spectral range of interest can be retrieved by using corresponding spectral PSF. The regional and spectral PSFs are fixed and only need to be recorded once for all time use. We utilizes the imager to its full capacity both in terms of dimension and dynamic range to enable an unique imaging technique which goes beyond the capabilities of common lens imaging systems. aperture, and multispectral imaging.

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