Extending the depth-of-field of imaging systems with a scattering diffuser

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Large depth of field (DOF) is a longstanding goal in optical imaging field. In this paper we presented a simple but efficient method to extend the DOF of a diffraction-limited imaging system using a thin scattering diffuser. The DOF characteristic of the imaging system with random phase modulation was analyzed based on the analytical model of ambiguity function as a polar display of the optical transfer function (OTF). The results of numerical simulation showed that more high-frequency components existed in the defocused OTF curve when the exit pupil of the imaging system exhibited a random phase modulation. It proved the important role of the scattering diffuser in extending the DOF of imaging systems. For the reconstruction, a stack of point spread functions (PSFs) corresponding to different axial locations within a measurement range were superimposed to construct the stacked PSF. Then the large DOF image was recovered from a speckle pattern by deconvolution. In this proof-of-concept, we experimentally demonstrated the single-shot imaging with larger DOF using a thin glass scattering diffuser in both a single-lens imaging system and a microscopic imaging system.

The depth-of-field (DOF) of an imaging system refers to the range in the scene that will appear in focus. The parts of the image that lie outside the DOF tend to be blurred and less sharp. Optical imaging with a large DOF is a longstanding goal with important applications in varied fields1–4. In general, the increase of DOF are associated with a reduction of the numerical aperture or the use of an optical power absorbing apodizer5. However, it leads to degrading of the optical power at the image plane and decrease of resolution. To overcome these limitations, a variety of techniques have been proposed over the past years. One representative is image fusion where several images of the same scene are acquired while different parts of the object are focused on3,6. But it is time-consuming and multiple-exposure is not applicable to dynamic scenes. Another promising technique is wavefront coding, in which the incoherent optical system is modified using a cubic-phase mask (or other special phase mask). As a result, the point spread function (PSF) is not sensitive to defocusing7–14. However, the phase masks need to be specially designed and fabricated, which is much difficult as the phase mask has spatially varied thickness and is combined with non-rotationally symmetric aspheric optical elements. Furthermore, the optical recording process requires an accurate alignment of these special phase masks since the decenter and tilt may degrade the imaging performance15.

Imaging of objects within or hidden behind diffusing media is challenging due to severe degradation in image quality caused by random scattered light. Continuous efforts have been invested to find a solution to seeing through a scattering medium16–19. On the other hand, a scattering medium has been considered as a helpful optical element20–27 for imaging instead of an undesirable obstacle in recent years. As reported in literature, scattering improved the sharpness of the focus via spatial wavefront shaping20; a randomly scattering high-index medium successfully enhanced the resolution of wide-field fluorescence microscopy21; the scattering matrix measurement realized the reference-free holographic imaging22; the spectral decorrelation effect in scattering media resulted in single-shot multispectral imaging23; the use of scattering media could also achieve 3D imaging24,25 and lensless microscopy26; DiffuserCam achieved lensless 3D imaging with a well-designed architecture and compress sensing algorithm27. Among these works mentioned above, few showed the ability to extend DOF.
Speckle-correlation-based imaging experimentally demonstrated the property of infinite DOF\textsuperscript{28} but no axial sectioning capability. Recently, some contributions have been made to depth-resolved and DOF-extended imaging through scattering media, such as phase space measurement\textsuperscript{29}, PSF manipulation\textsuperscript{30}, light field estimation\textsuperscript{31} and coherence gating\textsuperscript{32}. Nevertheless, their practical application is limited by complex experimental setup and tedious calculation.

Here, we presented a simple but efficient technique to extend the DOF of an incoherent diffraction-limited imaging system using a thin scattering diffuser such as a common ground glass. The DOF characteristic of the imaging system with scattering medium was analyzed based on the analytical model of the ambiguity function as a polar display of the optical transfer function (OTF). It showed more high-frequency components were collected by the scattering medium, which were normally lost with defocusing in traditional lens-based imaging systems. Experiments demonstrated large DOF images could be reconstructed using the PSF stack calculated from a sequence of PSFs.

**Principle and Method**

**Analysis on the DOF characteristic of the imaging system with a scattering diffuser.** For the sake of simplicity and without loss of generality, we consider an example of a single-lens imaging system. Assume a thin scattering diffuser is a random pure phase function, in normalized coordinates, that is

\[
P(x) = \begin{cases} \exp[j2\pi R(x)], & |x| \leq 1 \\ 0 & \text{otherwise} \end{cases}
\]

where \( x \) is the normalized pupil coordinate, \( R(x) \) is a random distribution in the range between \([0,1]\). Thus the generalized pupil function, as a function of misfocus, can be expressed as

\[
Q(x) = P(x)\exp[jkW_{20}x^2]
\]

where \( k \) is the wave number and \( W_{20} \) denotes the misfocus aberration constant. According to Hopkins criterion\textsuperscript{5}, the one-dimensional defocused optical transfer function (OTF) that takes misfocusing into account is:

\[
H(u; W_{20}) = \int Q\left( x + \frac{\mu}{2} \right)\exp[j2\pi(x - \frac{\mu}{2})]dx = \int P\left( x + \frac{\mu}{2} \right)\exp[j2\pi\left( \frac{2W_{20}}{\lambda} \right)x]\frac{dx}{\mu}
\]

where \( \lambda \) is the wavelength of the illuminated light, \( \mu \) denotes spatial frequency coordinate. On the other hand, the ambiguity function (AF) in the phase space is defined as:

\[
A(u; y) = \int P\left( x + \frac{\mu}{2} \right)\exp[j2\pi xy]dx
\]

where \( y \) denotes the normalized coordinate. Based on comparison of Eqs (3) and (4), the two-dimensional AF can be regarded as a polar representation of the one-dimensional OTF of a rectangular separable incoherent optical system with the focus error as variable\textsuperscript{33–35}, that is:

\[
H(\mu; W_{20}) = A\left( \mu; \frac{2W_{20}}{\lambda}\mu \right)
\]

In such way, AF could be used as an analytical tool that allows us to observe the OTF for all values of misfocus simultaneously. Numerical simulations were carried out to explore OTF’s statistical properties. An incoherent optical system with a one-dimensional rectangular aperture was taken into account. The corresponding two-dimensional AF of the exit pupil function is shown in Fig. 1(a). From Eq. (5), the defocused OTFs of the standard optical system with three different levels of defocusing \((W_{20} = 0, W_{20} = 2\lambda \text{ and } W_{20} = 20\lambda)\) were calculated. The results are shown in Fig. 1(b), where the horizontal and vertical axis denote the normalized spatial frequency and magnitude of the OTF, respectively; red, blue and green curves present the magnitude of OTFs without defocus \((W_{20} = 0)\), with slight defocus \((W_{20} = 2\lambda)\) and with severe defocus \((W_{20} = 20\lambda)\), respectively. The high-frequency components became increasingly smaller with the increase of the defocusing. In the proposed imaging system, a scattering diffuser with random phase was inserted as the exit pupil function and its two-dimensional AF is shown in Fig. 1(c). Similarly, we plotted the defocused OTFs for the same amounts of defocus as shown in Fig. 1(d). Compare the green line in Fig. 1(b,d), a random character but more high-frequency components were found in the severe defocused OTF curves. It indicated that the scattering medium contributed to collection of more high-frequency components that were lost with defocusing in traditional imaging systems. Therefore, a thin scattering diffuser could be consider as a helpful optical element for extending the DOF of a standard lens-based imaging system.

**Extending the DOF of an imaging system with a thin scattering diffuser.** This section describes how to extend the DOF of a diffraction-limited imaging system using a thin scattering diffuser. In a standard lens-based imaging system, a thin scattering diffuser as an element was placed at the exit pupil. When light illuminating the object, passes through the lens, the scattering diffuser, and finally forms a speckle pattern at the camera plane. Under incoherent illumination, the light from nearby points within the range of “memory effect” on the object is scattered by the thin diffuser, resulting in highly correlated but shifted PSFs that are formed on the output plane\textsuperscript{33–35}. Then the recorded speckle pattern is simply a superposition of these identical shifted PSFs. Therefore, the system with a thin scattering diffuser is approximately regarded as an incoherent imaging system, the speckle...
pattern intensity $I$ is nearly equal to the convolution of the object $O$ with the intensity PSF $S$, i.e. $I = O \ast S$. If objects are located at $n$ different axial positions $z$, the recorded speckle pattern can be written as

$$I = \sum_{z=1}^{n} I = \sum_{z=1}^{n} (O \ast S_z) = \sum_{z=1}^{n} O \ast S_z + C$$

(6)

where the symbol “$\ast$” and “$\sum$” are the convolution and matrix addition operation, $C$ denotes the sum of all the convolution cross terms, which should be approximately flat when $n$ is big enough due to the cross terms are different for the different PSFs. When a set of PSFs (PSF stack) corresponding the $n$ axial positions in the whole measurement range are recorded in advance (it is reasonable because the scattering diffuser is employed intentionally as an optical element into the imaging system), all the object $O$ located at different axial planes can be recovered from its speckle pattern $I$ with the overlays of all the PSFs by deconvolution:

$$O \approx F^{-1} \left[ \frac{F[I]}{F[S_z]} \right]$$

(7)

where $F$ and $F^{-1}$ denote 2D Fourier transform and 2D inverse Fourier transform, respectively. Moreover, as the axial positions of the whole calibrated PSF stack are known in advance, that allows to retrieve each layer of object with the corresponding depth information.

**Experimental Verification**

We carried out experiments to demonstrate extended DOF imaging with a scattering diffuser in both a single lens system and a microscopic system. The experimental setup of single lens system is presented in Fig. 2(a). The spatially incoherent illumination was composed of a laser ($\lambda = 532$ nm) and a rotated scattering diffuser. To attain a relatedly wide field of view (FOV), a thin ground glass (DG20-220-MD, Thorlabs) was selected as the scattering diffuser element in the experiments. The camera was a high dynamic range CMOS (PCO edge 5.5, 2160 × 2160 pixels with a pixel size of 6.5 × 6.5 $\mu$m). $L_1$ and $L_2$ denote the collimating lens and the imaging lens, respectively. The focal length of the imaging lens $L_2$ was $f = 15$ cm. $u$ and $v$ denote the object distance and image distance, respectively. When the object and camera were placed at the distances $u = 60$ cm and $v = 20$ cm on the opposite
Figure 2. Experimental set-up and PSF calibration. (a) Schematic of optical experimental setup. (b) The calibrated PSFs in the measurement range and the stacked PSF by superimposing these calibrated PSFs.

## Optical Experimental Setup

### Figure 4(a)

- **L1 and L2**: Imaging lenses.
- **RD**: Reference plane.
- **Object**: Sample to be imaged.
- **Diffuser**: Scattering element.
- **Camera**: Detector to record images.
- **Spatial incoherent illumination**: Light source.
- **M1 and M2**: Mirrors.

### Figure 4(b)

- **Pinehole planes**: Pinhole arrangement for deconvolution.
- **Calibrated PSFs**: Individual point spread functions.
- **Stacked PSF**: Combined PSF for reconstruction.

This figure illustrates the experimental setup for PSF calibration and reconstruction. The calibrated PSFs are generated by superimposing the individual PSFs, and the stacked PSF is used for the final reconstruction of images.

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**Equation:**

\[ \Delta z = \frac{\lambda f}{nN_A^2} \]

**Description:**

- \( \Delta z \): Defocused distance
- \( f \): Focal length of the lens
- \( \lambda \): Wavelength of the light
- \( n \): Refractive index of the medium
- \( N_A \): Numerical aperture of the objective

The relationship above describes the defocus distance \( \Delta z \) based on the Gaussian thin lens formula for a microscope objective.
Figure 3. Imaging a planar object located at different axial position. (a–c) Conventional imaging of a planar object placed at various axial position. (d–f) The raw camera images obtained with a modified imaging system with a scattering diffuser. (g–i) The reconstructed images by deconvolution.

Figure 4. Imaging two objects at different positions along the optical axis. (a) Schematic of experimental setup. (b) Images obtained with a conventional imaging system without and with diffuser. (c) The recorded PSFs and the reconstructed images. (d) The reconstructed results in 3D coordinates.
visualize the DOF extension, we show a line plot across the conventional image and the reconstructed image in Fig. 5(d). The DOF extension in microscopic imaging means that the working distance in microscopy could be enlarged, allowing more flexibility. The proposed method can be applied with higher NA objective lens under the diffraction-limit, but a smaller size pinhole and a higher power light source are needed to obtain a more accurate PSF for calibration thus allow for more reliable image reconstruction.

One of the feature of the proposed method is that there is no need to position the scattering diffuser accurately and just keep it unchanged during PSFs recording and speckle pattern measurement. Furthermore, the proposed method was demonstrated only in a transmission model and the imaging system was illuminated by a spatial incoherent light. The reflection model and the white light illumination need to be considered in the further research.

Conclusion

In summary, we experimentally demonstrated a simple but effective method to extend the DOF of an imaging system. By introducing a thin scattering diffuser (such as a common ground glass) into the spatial incoherent imaging system, one can acquire the images with a larger DOF. Theoretical analysis was carried out by using the model based on the similarity between the optical transfer function and the ambiguity function. The statistical properties of the defocused OTF were analyzed by numerical simulations. Owing to the random scattering properties of the scattering diffuser, more high-frequency components that were lost with defocusing in conventional imaging could be collected. Although the detected image is a speckle pattern, the clear image could be easily recovered by using deconvolution with the calibrated PSF. The proposed approach does not require to design and fabricate special phase masks. Its effectiveness and robustness for extending the DOF were experimentally verified in both single-lens and microscopic imaging systems.

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**Author Contributions**

M.L. and D.L. designed the initial experiments. M.L., D.L. and G.P. discussed the experimental implementation. M.L. preformed the simulations and experiments. D.L. W.H. and X.P. discussed the results. X.P., W.O., and G.S. conceived the idea and supervised the project. All authors contributed to the manuscript.

**Additional Information**

**Competing Interests** The authors declare no competing interests.

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