Analysing lateral resolution of a coherent single random phase encoding lensless imaging system under a correlation-based criterion

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Abstract: We overview the assessment of lateral resolution of a single random phase encoded lensless system under a correlation-based criterion. The lateral resolution of this system was compared with that of an equivalent lens-based imaging system.

1. Overview

In this paper, we overview recent reports [1] on the lateral resolution of a coherent single random phase encoded (SRPE) lenses imaging system (Fig. 1(a)) under a correlation-based lateral resolution criterion. Diffuser-based SRPE lensless imaging systems [1-5], due to the absence of bulky optical elements such as microscope objective lenses and mirrors, are more portable, compact than their lens-based counterparts and allow imaging with enhanced field-of-view, depth-of-field and spatial-frequency bandwidth. Coupled with deep neural networks, SRPE systems have been shown to be successful at cellular disease classifications [3-5] even when the number of pixels in the acquired intensity images were significantly reduced [5]. However, due to the acquired intensities of such systems being pseudorandom patterns (see Fig. 1(b)), it is challenging to assess their lateral resolution, a quantity (of prime importance) which has historically been defined visually by Rayleigh criterion [6], Sparrow criterion [7] etc. A purely correlation-based criterion which is founded on the same underlying principle (the capability of a system to differentiate two closely-placed point-sources) generalizes the above criteria towards lensless imaging systems and allows us to compare them with equivalent lens-based imaging systems. We have used numerical simulation to propagate the field emerging from two point-sources to the sensor plane of an SRPE lensless imaging system according to the principle of angular spectrum propagation (ASP) [8]. As the separation between the point-sources increases, the acquired intensity exhibits decreasing correlation with the intensity corresponding to two overlapping point-sources. Our proposed resolution criterion plots this correlation (Frobenius norm in this case) as a function of the separation between the point sources and identifies the separation at which the correlation drops to 35% of its maximum value as the lateral resolution of the imaging system. We computed the lateral resolution of an equivalent lens-based system (Fig. 1(c)) under the same definition and our results show that the lateral resolution does not suffer if we replace the lens with a diffuser. Moreover, the diffuser-based SRPE lensless imaging system shows robustness to various physical parameters.

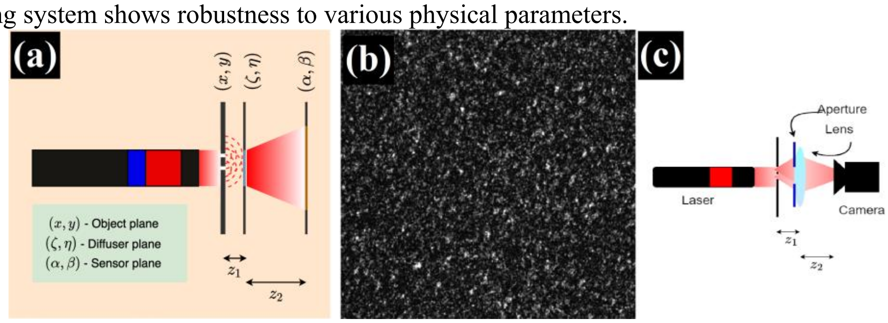

Fig.1. (a) Our SRPE lensless imaging system, (b) a sample intensity pattern acquired with SRPE system and, (c) an equivalent lens-based imaging system.

As shown in Fig. 1(a), our SRPE lensless imaging system consists of a laser diode that emanates a coherent optical field, a microscope glass slide at the object plane on which the sample under the observation is placed, a diffuser that spatially phase-modulates the field transmitting through the object, and an image sensor that captures the intensity of the modulated field. The physical dimension of the diffuser limits the highest spatial frequencies that can be captured by the device according to the following equation:

$$f_{xm} = \frac{1}{\lambda}\cos\theta_{xm} = \frac{\frac{D_\zeta}{2}}{\lambda\sqrt{z_1^2 + \frac{D_\zeta^2}{4}}}, f_{ym} = \frac{1}{\lambda}\cos\theta_{ym} = \frac{\frac{D_\eta}{2}}{\lambda\sqrt{z_1^2 + \frac{D_\eta^2}{4}}} \quad (1)$$

In Eq. (1), λ is the wavelength of the illuminating light, z_1 is the distance from the object plane to the diffuser plane, (D_ζ, D_η) are the dimensions of the diffuser along horizontal and vertical directions, $(\theta_{xm}, \theta_{ym})$ are the angles of the terminal rays of the diffuser along horizontal and vertical direction and, (f_{xm}, f_{ym}) are the maximum spatial frequencies captured by the diffuser along horizontal and vertical directions. To form an equivalent lens-based system, the object-to-lens distance was kept the same as the object-to-diffuser distance, the lens-to-sensor distance was kept the same as the diffuser-to-sensor distance, the aperture of the lens was kept the same as the aperture of the diffuser and the focal length of the lens was kept as $f_l = z_1 z_2/(z_1 + z_2)$ where z_1 is the object-to-lens distance and z_2 is the lens-to-sensor distance.

Using our correlation-based lateral resolution criterion, for a wavelength of 600 nanometers, an object to diffuser distance of 3.6 millimeters, a diffuser to image-sensor distance of 26.7 millimeters, sensor pixel-size of 0.6 microns, diffuser-size of 7.5 millimeters and, sensor-size of 7.5 millimeters, the resolution of our SRPE system was found to be 0.44 microns (see Fig. 2(a)) whereas that of the equivalent lens-based system was found to be 0.4 microns (see Fig. 2(b)). We also analyzed the effect of various physical parameters of the SRPE system on its lateral resolution and it was found to be robust against diffuser-to-sensor distance, sensor pixel-size and number of pixels.

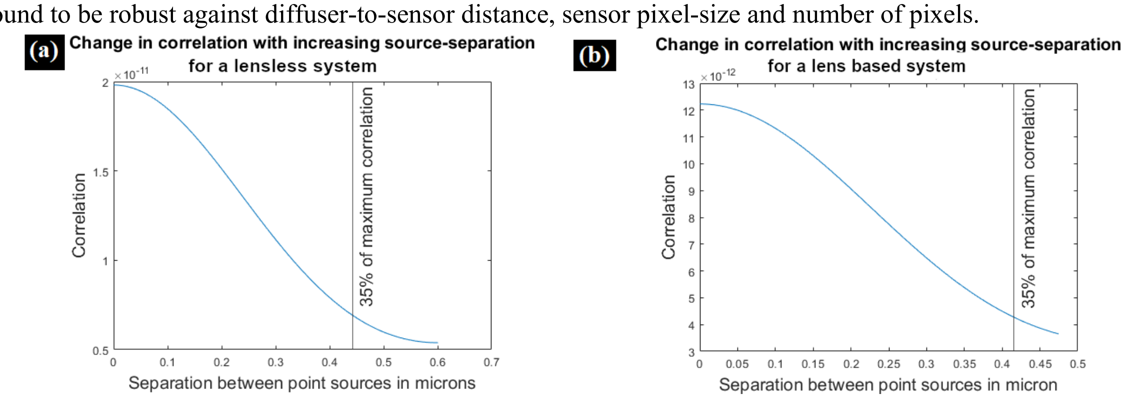

Fig.2. Lateral resolution estimates for (a) lensless imaging system under study and (b) an equivalent lens-based imaging system.

2. Conclusion

In summary, we overview the theoretical assessment of the lateral resolution of an SRPE lensless imaging system under a correlation-based criterion. When compared with an equivalent lens-based imaging system, our lensless system offers comparable lateral resolution with the added advantage of robustness to various system parameters. The presented analysis may benefit a variety of applications [9-10]. The authors acknowledge support by Air Force Research Laboratory, Materials and Manufacturing Directorate (AFRL/RXMS) (Contract No. FA8650-21-C-5711), Office of Naval Research N000142212375, and National Science Foundation Award Number (FAIN) 2141473.

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