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Mid-infrared Incoherent Three-Dimensional Imaging Using Lucy-Richardson-Rosen Algorithm

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Abstract: Two computational reconstruction methods namely the Lucy-Richardson algorithm and non-linear reconstruction have been combined to develop Lucy-Richardson-Rosen algorithm. This new algorithm has been used to convert a two-dimensional infrared spectral map into a three-dimensional image.

1. Introduction

Computational imaging methods have been rapidly advancing in the field of imaging over the past several years [1]. In this research area, coded aperture imaging (CAI) methods enable multidimensional and multispectral imaging capabilities with fewer resources [2-4]. In most of the CAI methods, an optical modulator is necessary in order to transform the object information into an intensity distribution that is recorded and computationally reconstructed back into the object information. It is computationally possible to deblur object information recorded using lenses with spatial or spectral aberrations [5,6]. However, the extent of deblurring is often limited to a small ratio between the axial error and the object-image distances. This is one of the main reasons why a lens has not been used so far as a coded aperture for 3D imaging. However, if a lens can be implemented as a coded aperture, then at least one plane of the object is not required to be computationally reconstructed. In other words, direct imaging and indirect imaging can co-exist. So, what prevented the implementation of a lens as a coded aperture? In our recent study, we have shed light on this topic [7]. In indirect imaging mode, the lateral resolution of the imaging system is given by the width of the autocorrelation function of the point spread function (PSF) which is low when the spatial and spectral aberrations are higher for a lens.

During our synchrotron beamtime experiment on the Infrared Microspectroscopy (IRM) beamline at the Australian Synchrotron, CAI method was attempted for the first-time using Fresnel zone aperture and scattering mask, which were fabricated on CaF_2 and BaF_2 substrates using femtosecond direct ablation. The method was implemented based on both the synchrotron IR mapping data and the offline IR imaging data obtained using an internal IR light source. Due to the high photon budget requirement in CAI, the signal-to-noise ratio was low. During this study, we observed that the Cassegrain objective lenses in the FTIR microscope generated strange 3D intensity distributions. The PSFs corresponding to non-imaging planes appeared as ring-like patterns with four distinct sharp peaks which produced a sharp autocorrelation function over a large depth. Consequently, Cassegrain objective lenses were used as coded apertures for 3D imaging with two imaging modes: direct, when the imaging conditions are satisfied and indirect, when reconstructed using deconvolution with pre-recorded PSFs. The above two imaging modes coexist. In this manuscript, the reconstruction method and experimental results are presented.

2. Methods

The most simplified configuration of an optical microscope is shown in Fig. 1(a), with a point object and a diffractive equivalent of a Cassegrain objective lens (DE-COL). The ring-shaped aperture and mounts of the DE-COL are responsible for the generation of the ring pattern and sharp intensity spots respectively. In linear, shift-invariant system, the intensity distribution of an object O can be expressed as $I_O = O \otimes PSF$. The reconstruction of O from I_O and PSF can be achieved using many methods, such as cross-correlation, maximum likelihood estimation, and regularization [8]. In this study, the widely used maximum likelihood estimation method developed by Lucy [9] and Richardson [10], and non-linear reconstruction method of Rosen [11] were combined to create a novel reconstruction method Lucy-Richardson-Rosen algorithm (LRRA) [12]. The schematic of the algorithm is shown in Fig. 1(b). The LRRA requires to optimize three parameters (α, β and iterations). The recorded and spectrally averaged (765 channels) intensity distributions of PSF from direct mode $\Delta z = 0$ to $\Delta z = 150$ μm in steps of 50 μm are shown in Fig. 1(c). The blurred image of a silk sample and its' reconstruction result using LRRA (α = 0.5, β = 1, iterations = 18) are shown in Fig. 1(d). The two silk fibers that appeared blurred in the raw image were refocused computationally.

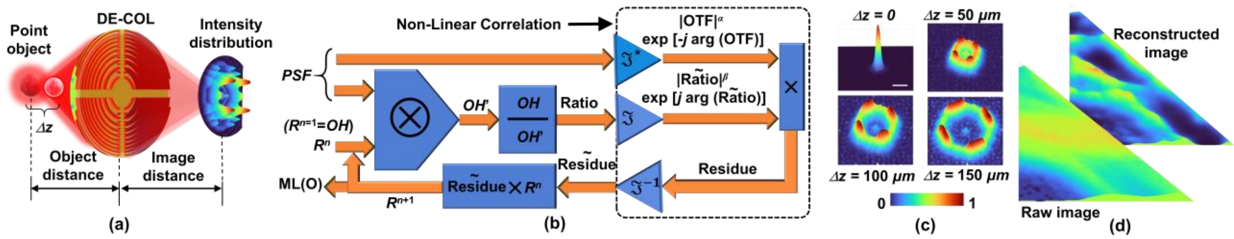

Figure 1. (a) Optical configuration of the imaging system. (b) Schematic of the LRRA. (c) Images of the spectrally averaged PSFs recorded at $\Delta z = 0$ to $\Delta z = 150$ µm in steps of 50 µm. (d) Recorded and spectrally averaged image of silk sample and reconstructed image using LRRA and the recorded PSF for α = 0.5, β = 1, iterations = 18.

3. Discussion and Conclusion

In this study, we have converted a 2D map into a 3D image using computational imaging principles. A new reconstruction method LRRA has been developed by combining two well-known reconstruction methods (i.e. Lucy-Richardson algorithm and non-linear reconstruction). The preliminary results were found to be promising. We believe that the application of LRRA is not limited to the intensity distributions generated by Cassegrain objective lenses, but also many deterministic fields [7]. The LRRA will be useful for applying many deterministic fields for imaging and also for information extraction from optical security systems.

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