Extraordinary Computational Imaging Technologies with Ordinary Optical Modulators (Invited)

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Abstract: Computational imaging technology (CIT) has revolutionized the field of imaging. CITs based on two genres namely random and deterministic optical fields generated by common optical modulators with extraordinary imaging capabilities are discussed.

1. Introduction

In the past, the performance of a direct imaging system relied completely on the performance of the optical element causing a severe load on the manufacturing technologies and at the same time increased the cost and size of the imaging systems [1]. The development of signal processing tools and fast computers led to the advent of computational imaging technology (CIT) relaxing the above stringent dependency on optical element and sharing the imaging task with a computational algorithm [2,3]. The collaboration between optics and computation made the imaging system an indirect one consisting of two steps: optical recording and computational reconstruction [4]. In the recording step, the light from an object was modulated by an optical modulator which maps the object intensity to a special intensity distribution. In the reconstruction step, the recorded intensity distribution is reconstructed in the computer into the image of the object using a computational reconstruction algorithm. The type of computational reconstruction algorithm depends upon the optical modulator used in the system. The optical modulators can be broadly classified into deterministic optical field generators and random ones. In the recent years, CITs with both random optical modulators [5] and deterministic ones [6] have gained significant attention due to the interesting characteristics they demonstrated such as sharp autocorrelation functions equal to the diffraction limited spot size and low cross-correlation values with changes in depth or wavelength. In this study, two cases of incoherent CITs with commonly available random [7, 8] as well as deterministic optical modulators [9] capable of performing extraordinary imaging are presented.

2. Methods

In this study, only shift-invariant systems that are linear in intensity whose imaging characteristics can be completely characterized by the point spread functions (PSFs) are considered. The optical configurations are shown in Fig. 1(a). The object intensity distribution can be expressed as $I_O = PSF \otimes O$, where 'O' is the object function and '⊗' is a 2D convolutional operator. The image of the object was reconstructed by a cross correlation between the recorded object intensity distribution and the PSF given as $I_R = I_O * PSF = O \otimes PSF * PSF = O \otimes \Lambda$, where Λ is a delta-like function obtained by the autocorrelation of the PSF and '*' is the 2D correlation operator. The above correlation can be implemented as a matched filter, phase-only filter, Weiner filter and non-linear reconstruction [4].

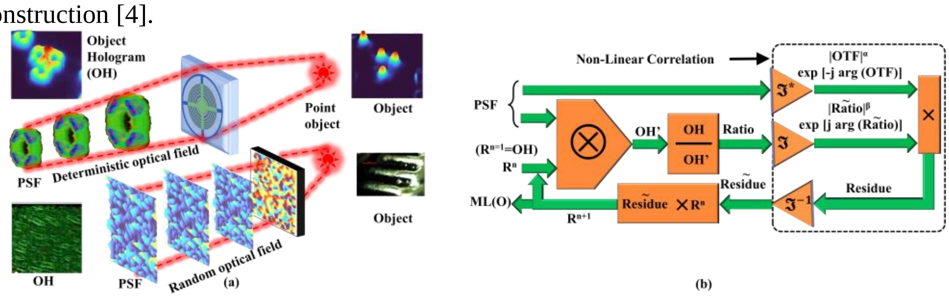

Figure 1 (a) Optical configuration of a CIT with deterministic and random optical field. (b) Schematic of Lucy-Richardson-Rosen algorithm with non-linear correlation indicated by the dotted box; $\mathfrak{I}$ – Fourier transform operator; OTF – optical transfer function; R^n – n^{th} solution; ML – Maximum likelihood, α and β are the powers of the magnitude of the $\mathfrak{I}$ of matrices which are tuned between -1 to +1.

In the recent studies on scattering based CITs [4], it was shown that the non-linear reconstruction performed better than the other filters. However, in the case of CITs with deterministic fields, the performance of non-linear correlation was not satisfactory. In a recent study, the maximum likelihood iterative algorithm developed by Lucy [10] and Richardson [11] was modified by introducing the non-linear reconstruction developed by Rosen as shown in Fig. 1(b). The introduction of non-linearity into Lucy-Richardson algorithm significantly increased the convergence speed of Lucy-Richardson by more than an order and improved the estimation.

3. Experiments

An experiment was demonstrated on the two genres: random and deterministic optical fields. In the first experiment, CIT was applied to convert a high-speed 2D monochrome camera (Phantom v2512) into a high speed colour 3D camera using a mask containing a random array of pinholes as the optical modulator and non-linear reconstruction method. In the second experiment, the Bruker's infrared microspectrometry unit was converted into a 3D microspectrometry unit using the Cassegrain objective lens as the optical modulator and Lucy-Richardson-Rosen algorithm. The 3D image of the spark, the recorded image of a silk sample, reconstructed image at a different depth and the direct imaging result at the same depth are shown in Figs. 2(a)-(d) respectively.

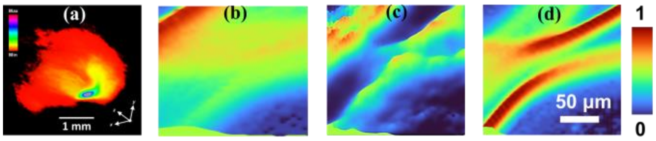

Figure 2. (a) 3D image of a spark. (b) Recorded image of a silk sample, (c) reconstructed image of the silk sample at a different depth and (d) the image obtained by direct imaging method by refocusing at the same depth.

4. Discussion and conclusion

CITs has been proven to expand the imaging characteristics beyond the conventional limits. In addition to increasing the number of imaging dimensionalities and imaging beyond the physical limitations – color imaging with monochrome sensors, CITs have also been proven to increase the field of view, resolving power and reduce the cost of imaging systems. In the invited talk, the indirect imaging concepts of CITs and the two experiments using common optical modulators for high-speed imaging and infrared microspectrometry will be presented.

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