Digital Holography and 3-D Imaging (DH) 2022 © Optica Publishing Group 2022

Incoherent Digital Holography using Spiral Rotating Point Spread Functions Created by Double-helix Beams

Nitin Dubey,[1] Vijayakumar Anand,[2,3] Svetlana Khonina,[4,5] Ravi Kumar,[1] Andra Naresh Kumar Reddy,[6,7] and Joseph Rosen,[1]

[1]*School of Electrical and Computer Engineering, Ben-Gurion University of the Negev, P.O. Box 653, Beer-Sheva 8410501, Israel.*
[2]*Institute of Physics, University of Tartu, 50411 Tartu, Estonia.*
[3]*Optical Sciences Center and ARC Training Centre in Surface Engineering for Advanced Materials (SEAM), School of Science, Computing and Engineering Technologies, Swinburne University of Technology, Hawthorn, Melbourne, Victoria 3122, Australia.*
[4]*Samara National Research University, 443086 Samara, Russia.*
[5]*Image Processing Systems Institute—Branch of the Federal Scientific Research Centre, "Crystallography and Photonics" of Russian Academy of Sciences, 443001 Samara, Russia.*
[6]*Hee Photonic Labs, Riga, LV-1002, Latvia.*
[7]*Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 7610001, Israel.*
vijayakumar.anand@ut.ee

Abstract: A new incoherent 3D imaging system with a rotating point spread function has been developed. Different computational reconstruction methods such as non-linear reconstruction and the Lucy-Richardson-Rosen algorithm were tested, and their performances were compared.

1. Introduction

The advancements in incoherent holography have been accelerated by the development of active devices like spatial light modulators (SLMs) and computational and signal processing tools. Fresnel incoherent correlation holography (FINCH) [1] and coded aperture imaging (CAI) methods [2-4] are excellent examples that evolved in this way. In CAI and FINCH, the imaging process consists of two steps: optical recording and computational reconstruction. FINCH can exhibit super-resolution capabilities, while CAI has a simpler optical configuration than FINCH. For the above reason, CAI became more widely adapted to various applications than FINCH. Among different possibilities of aperture masks in CAI, the scattering mask that creates speckle pattern was preferred since the average speckle size is equal to the diffraction-limited spot size, and this mask had high sensitivity for depth and wavelength [5]. However, the main drawback was the astronomical photon budget requirements, which precluded the implementation in low-energy applications.

During the implementation of CAI based imaging technique in the infrared beamline of the Australian synchrotron [6], the light diffracted from Cassegrain objective lenses (COL) was found to possess four sharp intensity peaks over a considerable depth, exhibiting a sharp autocorrelation function over an extended depth with low cross-correlation values. This research led to the requirement for the 3D imaging of CAI as sharp autocorrelation and low cross-correlation along the depth (SALCAD). The chaotic CAI has a random SALCAD field, while COL generates a deterministic SALCAD field. A new algorithm for 3D image reconstruction was developed by combining the non-linear reconstruction method (NLR) proposed by Rosen [7] and the well-known Lucy-Richardson algorithm (LRA) [8,9] and named the Lucy-Richardson-Rosen algorithm (LRRA) [10].

A whole family of light beams carries the SALCAD property called orbital angular momentum (OAM) beams. In this study, we investigated the OAM beams with rotating intensity distributions along the depth axis [11,12], especially the one with a double helix pattern [13,14]. Due to the double helix beam, every point in the 3D image is converted into a double helix pattern. The particle's location can be identified by the rotation angle of the two spots. This approach improved the 3D localization. The proposed imaging system is termed 3D incoherent imaging using spiral beam ($3DI^2SB$).

2. Methodology

The optical configuration of $3DI^2SB$ includes the observed object, a multifunctional diffractive optical element, and the image sensor, as shown in Fig. 1(a). The schematic of the LRRA is shown in Fig. 1(b), where NLR has replaced the correlation in LRA. The distance between an object and DOE is z_s, and between DOE and the sensor is z_h. Every object point is converted into a double helix beam. The point spread function (I_{PSF}) was simulated for z_s from 15 cm to 45 cm in steps of 5 cm, as shown in Fig. 1(c). A test object "Structured light" was used, and the simulated intensity distribution (I_O) is shown in Fig. 1(c). The reconstruction results using NLR, LRA and LRRA are shown in Fig. 1(c). Evidently, LRRA performed better than LRA and NLR. An experiment was carried out using test objects elements 4, 5, and 6 (both digits and gratings) of group 5 of negative USAF target illuminated by a lightemitting diode. An SLM was used to display the DOE. During the experiment, NLR was found to perform better than both LRA and LRRA, as LRRA was found to be highly sensitive to displacement errors between PSF and object intensity patterns. The images of PSF, object intensity, and reconstruction results using NLR are shown in Fig. 1(d).

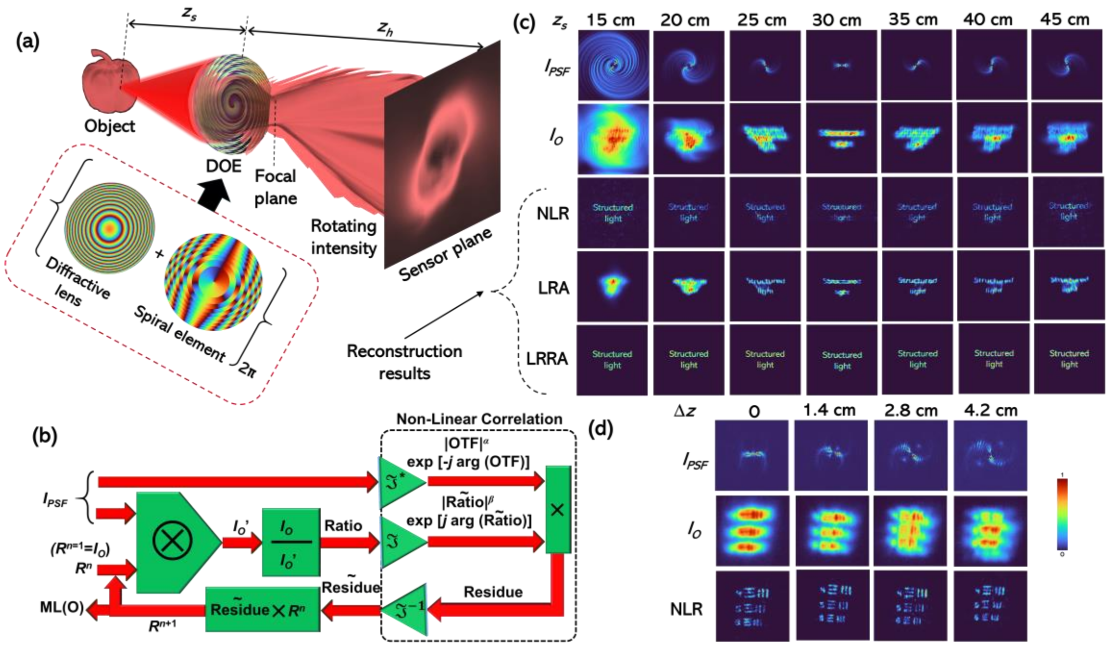

Figure. 1 (a) Optical configuration of 3DI²SB and generation of the phase distribution of the multifunctional diffractive optical element from a lens and spiral element. (b) Schematic of LRRA. (c) Simulation results of PSF, object intensity, and reconstruction results using NLR, LRA, LRRA for z_s = 15 cm to 45 cm in steps of 5 cm. (d) Experimental results of I_{PSF} and I_O and reconstruction results using NLR. OTF – Optical Transfer Function, ML – Maximum Likelihood and I_O – object intensity.

3. Discussion and conclusion

An incoherent 3D imaging technique 3DI²SB was developed. The image reconstruction was carried out using three different algorithms, namely NLR, LRA and LRRA. In the simulation, LRRA performed better than NLR and LRA, while in experiments, NLR performed better than both LRA and LRRA. Preliminary results are promising.

Acknowledgements European Union's Horizon 2020 research and innovation programme grant agreement No. 857627 (CIPHR).

References

[1] J. Rosen and G. Brooker, "Digital spatially incoherent Fresnel holography," Opt. Lett. **32**, 912-914 (2007).
[2] E. E. Fenimore and T. M. Cannon, "Uniformly redundant arrays: digital reconstruction methods," Appl. Opt. **20**, 1858-1864 (1981).
[3] A. Wagadarikar, R. John, R. Willett, and D. Brady, "Single disperser design for coded aperture snapshot spectral imaging," Appl. Opt. **47**, B44-B51 (2008).
[4] N. Dubey and J. Rosen, "Interferenceless coded aperture correlation holography with point spread holograms of isolated chaotic islands for 3D imaging," Sci. Rep. **12**, 4544 (2022).
[5] J. Rosen, A. Vijayakumar, M. Kumar, M. R. Rai, R. Kelner, Y. Kashter, A. Bulbul, and S. Mukherjee, "Recent advances in self-interference incoherent digital holography," Adv. Opt. Photon. **11**, 1-66 (2019).
[6] V. Anand, S. H. Ng, T. Katkus, J. Maksimovic, A. R. Klein, J. Vongsvivut, K. R. Bambery, M. J. Tobin, and S. Juodkazis, "Exploiting spatio-spectral aberrations for rapid synchrotron infrared imaging," J. Synchrotron Radiat. **28**, 1616–1619 (2021).
[7] M. R. Rai, A. Vijayakumar, and J. Rosen, "Non-linear adaptive three-dimensional imaging with interferenceless coded aperture correlation holography (I-COACH)," Opt. Express **26**, 18143-18154 (2018).
[8] W. H. Richardson, "Bayesian-Based Iterative Method of Image Restoration*," J. Opt. Soc. Am. **62**, 55-59 (1972).
[9] L. B. Lucy, "An iterative technique for the rectification of observed distributions," Astron. J. **79**, 745 (1974).
[10] V. Anand, M. Han, J. Maksimovic, S. H. Ng, T. Katkus, A. Klein, K. Bambery, M. J. Tobin, J. Vongsvivut, and S. Juodkazis, "Single-shot mid-infrared incoherent holography using Lucy-Richardson-Rosen algorithm," Opto-Electronic Sci. **1**, 210006 (2022).
[11] V. V. Kotlyar, S. N. Khonina, R. V. Skidanov, and V. A. Soifer, "Rotation of laser beams with zero of the orbital angular momentum," Opt. Commun. **274**, 8–14 (2007).
[12] C. Schulze, F. S. Roux, A. Dudley, R. Rop, M. Duparré, and A. Forbes, "Accelerated rotation with orbital angular momentum modes," Phys. Rev. A **91**, 043821 (2015).
[13] S. R. P. Pavani and R. Piestun, "Three-dimensional tracking of fluorescent microparticles using a photon-limited double-helix response system," Opt. Express **16**, 22048-22057 (2008).
[14] S. Prasad, "Rotating point spread function via pupil-phase engineering," Opt. Lett. **38**, 585-587 (2013).