Fresnel incoherent correlation holography with Lucy-Richardson-Rosen algorithm and modified Gerchberg-Saxton algorithm

Andrei Bleahu, Shivasubramanian Gopinath, Francis Gracy Arockiaraj, Aravind Simon John Francis Rajeswary, Saulius Juodkazis, et al.

Andrei Bleahu, Shivasubramanian Gopinath, Francis Gracy Arockiaraj, Aravind Simon John Francis Rajeswary, Saulius Juodkazis, Vijayakumar Anand, "Fresnel incoherent correlation holography with Lucy-Richardson-Rosen algorithm and modified Gerchberg-Saxton algorithm," Proc. SPIE 12574, Holography: Advances and Modern Trends VIII, 125740A (31 May 2023); doi: 10.1117/12.2680194

SPIE.

Event: SPIE Optics + Optoelectronics, 2023, Prague, Czech Republic

Fresnel Incoherent Correlation Holography with Lucy-Richardson-Rosen Algorithm and Modified Gerchberg-Saxton Algorithm

Andrei Bleahu,[a,†] Shivasubramanian Gopinath,[a,†,*] Francis Gracy Arockiaraj,[a,b,†] Aravind Simon John Francis Rajeswary,[a] Saulius Juodkazis,[c,d] Vijayakumar Anand[a,c]

[a]Institute of Physics, University of Tartu, W. Ostwaldi 1, 50411 Tartu, Estonia

[b]School of Electrical and Computer Engineering, Ben-Gurion University of the Negev, Beer-Sheva 8410501, Israel

[c]Optical Sciences Center, Swinburne University of Technology, Hawthorn, Melbourne, VIC 3122, Australia

[d]Tokyo Tech World Research Hub Initiative (WRHI), School of Materials and Chemical Technology, Tokyo Institute of Technology, 2-12-1, Ookayama, Meguro-ku, Tokyo 152-8550, Japan

[†]The authors contributed equally to this work

[*]shivasubramanian.gopinath@ut.ee

ABSTRACT

Fresnel incoherent correlation holography (FINCH) is a well-established incoherent digital holography technique for imaging objects with an enhanced transverse resolution. In FINCH, light from an object point is split into two and modulated using two different quadratic phase masks and interfered to obtain the self-interference hologram. The two beams can be generated either by spatial random multiplexing or polarization multiplexing, with the former being power efficient and the latter exhibits a high signal to noise ratio. At least three such holograms are recorded with phase shifts 0, 2π/3 and 4π/3 radians and combined to obtain a complex hologram. This complex hologram can be numerically propagated to reconstruct any plane of the object. Under special beam matching condition, FINCH can exhibit a transverse resolution that is 1.5 times better than incoherent lens-based direct imaging systems with the same numerical aperture. To summarize, FINCH records 3D information with a high resolution at the expense of reduced temporal resolution. Several techniques have been developed in the past to improve the temporal resolution of FINCH by sacrificing transverse resolution and field of view. In this study, a recently developed phase mask design algorithm called Transport of Amplitude into Phase based Gerchberg-Saxton Algorithm (TAP-GSA) and reconstruction algorithm called Lucy-Richardson-Rosen algorithm (LR^2A) has been implemented in FINCH. The modified approach with the TAP-GSA and LR^2A significantly improved the performance of FINCH with an improved temporal resolution, light throughput and signal to noise ratio.

Keywords: Super-resolution, Fresnel incoherent correlation holography, holography, Lucy-Richardson-Rosen algorithm, Gerchberg-Saxton algorithm

1. INTRODUCTION

Fresnel incoherent correlation holography (FINCH) is a widely used incoherent digital holography technique for imaging and fluorescence microscopy.[1,2] FINCH was developed in the year 2007 by Rosen and Brooker to image objects that are incoherently illuminated along three spatial dimensions.[3,4] In the first version of FINCH, two diffractive lenses with different focal distances were randomly multiplexed to form a multifunctional diffractive element (MDE) that can split incoming light into two and modulate them differently and create interference between them. Since, the incoming light is spatially incoherent, the interference can occur only as self-interference between light derived from the same object point that are differently modulated by the MDE. Since FINCH has an in-line configuration, three camera shots are recorded with different phase shifts 0, 2π/3 and 4π/3 radians between the two interfering waves and the three recordings are superposed to form a complex hologram. This complex hologram can be numerically backpropagated to reconstruct the object without the twin image and bias terms. The random multiplexing approach used for designing MDE generated random noises during reconstruction. A polarization multiplexing method was proposed to reduce the

Holography: Advances and Modern Trends VIII, edited by Antonio Fimia, Miroslav Hrabovský, Proc. of SPIE Vol. 12574, 125740A

background noise in FINCH at the expense of loss of light.[4] During this development, the super resolution capability of FINCH was also unveiled. The main drawback of FINCH is its temporal resolution which is one-third of a direct lens-based imaging system. Different spatial multiplexing methods,[5,6] polarization multiplexing methods,[7] numerical methods,[8] computational reconstruction methods[9,10] were developed to improve the temporal resolution of FINCH. However, all the above solutions always presented a penalty in the form of low field of view and SNR.

Recently, a new computational algorithm called Lucy-Richardson-Rosen algorithm (LR^2A)[11] was developed by combining Lucy-Richardson Algorithm (LRA)[12,13] and non-linear reconstruction (NLR).[9] Initially LR^2A was only applied to deconvolve blurred images recorded using infrared microscope at the Australian Synchrotron.[11] Later, it was found that LR^2A can be used to deconvolve many deterministic optical fields.[14,15] In this study, LR^2A has been implemented in FINCH in the same fashion as the above studies.[11-15] In the previous studies of FINCH in both spatial random multiplexing and polarization multiplexing there is a loss of optical power, with random multiplexing exhibiting a better power efficiency than polarization multiplexing.[16] Recently, a modified Gerchberg-Saxton algorithm (GSA) called Transport of Amplitude into Phase based GSA (TAP-GSA) to multiplex two diffractive lens functions without the need for random multiplexing. The developed TAP-GSA exhibited an improvement in light throughput by 2 and 1.5 times that of polarization multiplexing and random multiplexing respectively. In this study, the two new methods namely LR^2A and TAP-GSA have been used to improve the performance of FINCH.

2. METHODS

The generalized optical configuration of FINCH is shown in Figure 1. The light from an object point is collimated by a refractive lens L and incident on a spatial light modulator (SLM) on which an MDE with the functions of two diffractive lenses designed by TAP-GSA is displayed. The TAP-GSA algorithm is shown in Figure 2. The polarizer P_1 is oriented along the active axis of the SLM to achieve full beam modulation. At the SLM, two beams are generated which are then interfered at the sensor plane. To obtain super-resolution, it is necessary to keep the diameters of the two beams equal at the plane of recording of the hologram. In the conventional approach, at least three holograms are recorded and superposed into a complex hologram. The complex hologram is numerically propagated by a distance of $z_2/2$ to reconstruct the image of the object. To implement LR^2A (shown in Figure 3), in the first step, the point spread hologram (PSH) of FINCH is recorded and in the next step, the object hologram (OH) is recorded. The coefficients of NLR (α and β) part of the LR^2A and the number of iterations p were adjusted to obtain an optimal reconstruction from LR^2A. The red and green arrows indicate polarizer orientations during spatial and polarization multiplexing respectively. As it is seen, the polarizer P_2 is not required for spatial multiplexing but to have a generalized configuration, P_2 is retained.

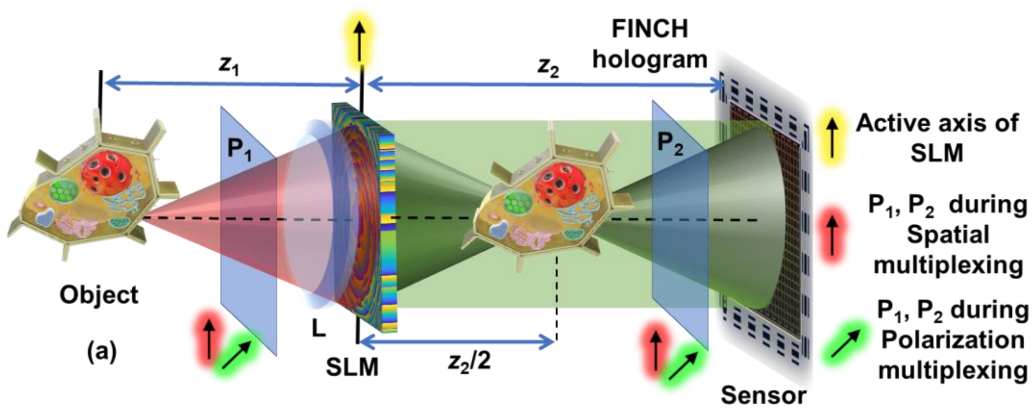

Figure 1. Schematic of the generalized FINCH configuration. Red color arrows and green color arrows indicate polarizer orientations during spatial and polarization multiplexing respectively.

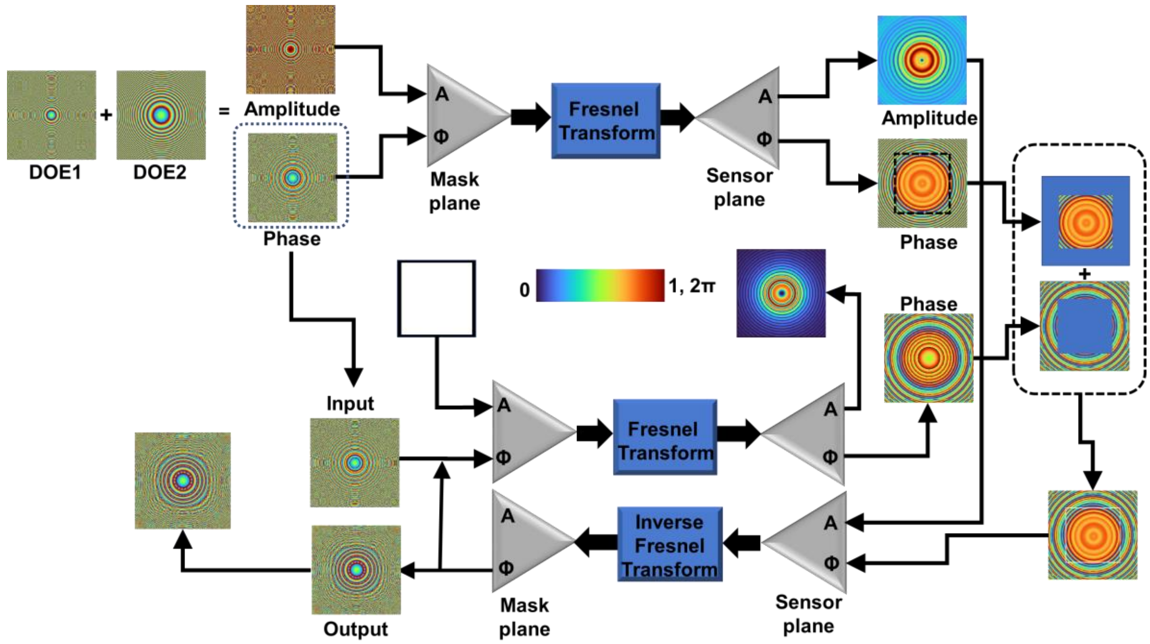

Figure 2. Schematic of TAP-GSA. DOE1 and DOE2 represent diffractive optical elements 1 and 2 that are combined using TAP-GSA.

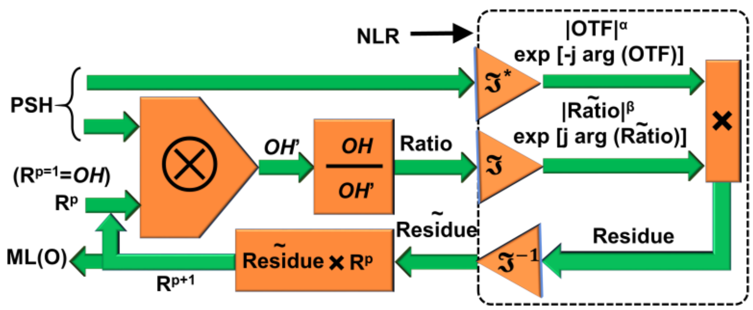

Figure 3. Schematic of LR^{2}A. ML – maximum likelihood; OTF – optical transfer function; p – number of iterations; ⊗ - 2D convolutional operator; OH – object hologram; $\mathfrak{I}$ - Fourier transform; * - complex conjugate, $^{-1}$ – inverse; R^{p+1} – (p+1)th solution, PSH – point spread hologram.

3. SIMULATION RESULTS

The United States Air Force (USAF) resolution target's image was used as the test object for simulation. A matrix size of 500 × 500 pixels was used, with λ = 650 nm and pixel size 10 μm. The FINCH configuration for optimal beam overlap was designed with z_1 = 50 cm, z_2 = 1 m. The DOE1 was a diffractive lens with a focal length of 25 cm and the DOE2 is a diffractive lens with a focal length of ∞ in the MDE. The TAP-GSA was used to combine the two DOEs. The direct imaging was achieved by replacing the MDE by a diffractive lens with a focal length of 33.3 cm. Two cases of FINCH were compared. In the first case, FINCH with conventional method of imaging consisting of three camera shots of phase-shifted holograms, combining them into a complex hologram and reconstruction is achieved by a numerical back propagation to one of the focal planes of DOEs. In the second case, a PSH is simulated using a point object and the OH is simulated for the test object and the image is reconstructed using LR^{2}A. The image of the test object is shown in Figure 4(a). The simulated direct imaging result is shown in Figure 4(b). The simulation result of conventional FINCH is shown in Figure 4(c). The simulation results of FINCH with LR^{2}A with PSH simulated using point objects with diameters 10 μm, 40 μm and 100 μm are shown in Figures 4(d)-4(f) respectively. As it is seen from Figure 4, when the PSH is simulated using large point objects, the results overlap with conventional FINCH. However, when the PSH was simulated for 10 μm which is also the sampling limit, the results are significantly better in the case of FINCH with LR^{2}A compared to conventional FINCH. FINCH in all cases have a better resolution than direct lens-based imaging which matches well with the theory of FINCH.

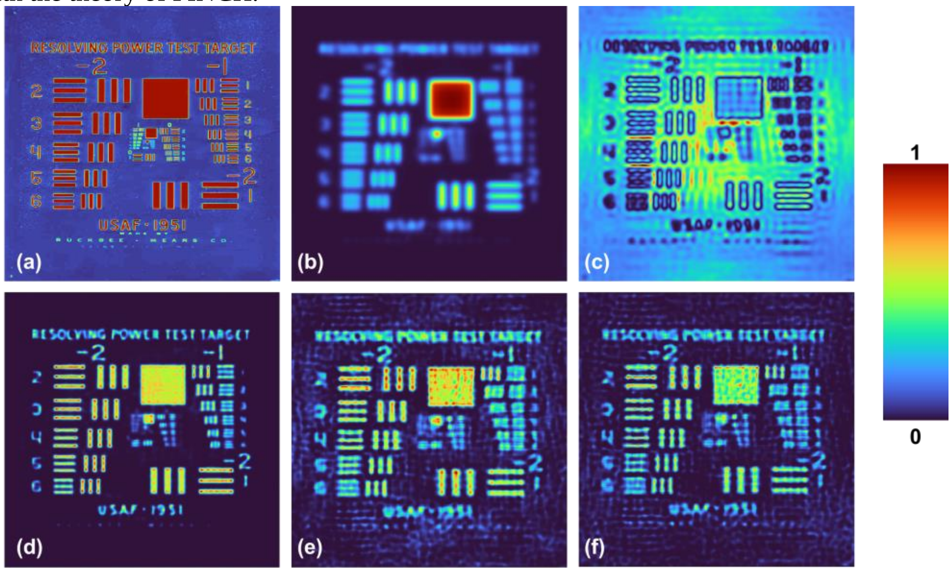

Figure 4. (a) Test object. Simulation results for (b) direct imaging, (c) conventional FINCH. FINCH with LR^{2}A with PSH simulated with a point object of diameter (d) 10 µm, (e) 40 µm and (f) 100 µm.

4. EXPERIMENTAL RESULTS

A preliminary experiment was carried out with a high-power LED (Thorlabs, 170 mW, λ = 650 nm and $\Delta\lambda$ = 20 nm), SLM (Thorlabs Exulus HD2, 1920×1200 pixels, pixel size = 8 µm) and an image sensor (Zelux CS165MU/M 1.6 MP monochrome CMOS camera, 1440×1080 pixels with pixel size ~3.5 µm). The light from the object was collimated using a refractive lens. The FINCH configuration was set up with diffractive lenses with focal lengths 14 cm and 25 cm to achieve optimal beam matching condition at a distance of 18 cm from the SLM. The PSH recorded using a pinhole with a diameter of 10 µm and the OH recorded using USAF object (Group – 5, Element 1) number 5 and gratings with a line width of 15.63 µm are shown in Figures 5(a) and 5(b) respectively. The reconstructed image obtained from LR^{2}A is shown in Figure 5(c).

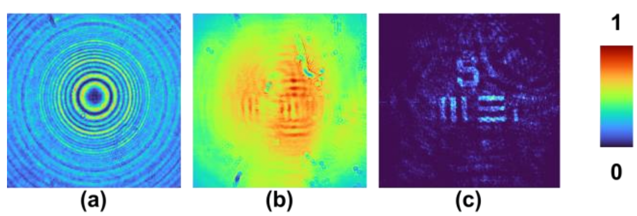

Figure 5. Experimental results. (a) PSH, (b) OH, (c) reconstruction result.

5. SUMMARY AND CONCLUSION

FINCH has been demonstrated with a single camera shot using LR^{2}A with an enhanced power throughput achieved using TAP-GSA. Two holograms were recorded, PSH with a pinhole and OH with the object. The image of the object was reconstructed by processing PSH and OH using LR^{2}A. The preliminary results are promising. The background noise present in the reconstruction is due to the change of conditions between recording of the PSH and OH. The dust particles seen in OH are not present in PSH. As seen in the simulation results, the performance of LR^{2}A depends on the quality of PSH. It is necessary to develop methods to measure or estimate PSH with a high accuracy.

Funding. AB thanks the French Institute Grant for High-Level Scientific Stay. We thank Etienne Brasselet, CNRS, University of Bordeaux, France, for his support regarding the optical experiments. This research was funded by the European Union's Horizon 2020 research and innovation programme, grant agreement No. 857627 (CIPHR).

REFERENCES

[1] Tahara, T., Zhang, Y., Rosen, J. *et al.* "Roadmap of incoherent digital holography," Appl. Phys. B. 128, 193 (2022).
[2] Rosen, J., Vijayakumar, A., Kumar, M., Rai, M. R., Kelner, R., Kashter, Y., Bulbul, A., Mukherjee, S., "Recent advances in self-interference incoherent digital holography," Adv. Opt. Photonics 11(1), 1–66 (2019).
[3] Rosen, J. and Brooker, G., "Digital spatially incoherent Fresnel holography," Opt. Lett. 32(8), 912-914 (2007).
[4] Brooker, G., Siegel, N., Wang, V. and Rosen, J., "Optimal resolution in Fresnel incoherent correlation holographic fluorescence microscopy," Opt. Express 19(6), 5047-5062 (2011).
[5] Nobukawa, T., Muroi, T., Katano, Y., Kinoshita, N., Ishii, N., "Single-shot phase-shifting incoherent digital holography with multiplexed checkerboard phase gratings," Optics Letters 43(8), 1698 (2018).
[6] Sakamaki, S., Yoneda, N., Nomura, T., "Single-shot in-line Fresnel incoherent holography using a dual-focus checkerboard lens," Applied Optics 59(22), 6612 (2020).
[7] Tahara, T., Kanno, T., Arai, Y., Ozawa, T., "Single-shot phase-shifting incoherent digital holography," Journal of Optics 19(6), 065705 (2017).
[8] Tahara, T., Kozawa, Y., Ishii, A., Wakunami, K., Ichihashi, Y., Oi, R., "Two-step phase-shifting interferometry for self-interference digital holography," Optics Letters 46(3), 669 (2021).
[9] Rai, M.R., Vijayakumar, A., and Rosen, J., "Non-linear adaptive three-dimensional imaging with interferenceless coded aperture correlation holography (I-COACH)," Opt. Express. 26(14), 18143-18154 (2018).
[10] Vijayakumar, A., Katkus, T., Lundgaard, S., Linklater, D. P., Ivanova, E. P., Ng, S. H., & Juodkazis, S., "Fresnel incoherent correlation holography with single camera shot," Opto-Electronic Advances, 3(08), 200004 (2020).
[11] Anand, V., Han, M., Maksimovic, J., Ng, S. H., Katkus, T., Klein, A., and Juodkazis, S., "Single-shot mid-infrared incoherent holography using Lucy-Richardson-Rosen algorithm," Opto-Electronic Science, 1(3), 210006-1 (2022).
[12] Richardson, W. H. "Bayesian-Based Iterative Method of Image Restoration*," J. Opt. Soc. Am. 62(1), 55-59 (1972).
[13] Lucy, L. B. "An iterative technique for the rectification of observed distributions," Astron. J. 79, 745 (1974).
[14] Praveen, P. A., Arockiaraj, F.G., Gopinath, S., Smith, D., Tauno, Kahro, Valdma, S.-M., Andrei, B, Ng, S. H., Reddy A. N. L., Katkus, T., Aravind, S. J. F. R, Rashid, A. G, Picker, S, Kukli, K., Tamm, A., Juodkazis, S., and Anand, V., "Deep Deconvolution of Object Information Modulated by a Refractive Lens Using Lucy-Richardson-Rosen Algorithm," Photonics 9(9), 625 (2022).
[15] Anand, V., Khonina, S., Kumar, R., Dubey, N., Reddy, A. N., Rosen, J., Juodkazis, S., "Three-dimensional incoherent imaging using spiral rotating point spread functions created by double-helix beams [invited]," Nanoscale Research Letters 17(1) (2022).
[16] Gopinath, S., Bleahu, A., Kahro, T., Rajeswary, A.S.J.F., Kumar, R., Kukli, K., Tamm, A., Rosen, J. Anand, V. Enhanced design of multiplexed coded masks for Fresnel incoherent correlation holography. 06 March 2023, PREPRINT (Version 1) [https://doi.org/10.21203/rs.3.rs-2617379/v1].