

NEWS & VIEWS

Open Access

Compressive holographic sensing simplifies quantitative phase imaging

Jiawei Sun^{1,2} and Juergen W. Czarske^{1,2,3,4}✉

Abstract

Quantitative phase imaging (QPI) has emerged as method for investigating biological specimen and technical objects. However, conventional methods often suffer from shortcomings in image quality, such as the twin image artifact. A novel computational framework for QPI is presented with high quality inline holographic imaging from a single intensity image. This paradigm shift is promising for advanced QPI of cells and tissues.

Digital holography has become a powerful non-destructive imaging technique in engineering, and biomedicine^{1–3}. Unlike traditional imaging techniques that only capture intensity information, holography provides both amplitude and phase information of the reflected or transmitted light field from an object. This feature enables the reconstruction of high-resolution, three-dimensional images that accurately represent the object's shape and structure with nanoscale precision. Nevertheless, a twin image is generated in the reconstruction process due to the complex conjugate nature of the digital holography⁴. The twin image is a significant problem in digital holography as it overlaps with and obscures the measured object, leading to reduced image quality and contrast. Such twin image problem can be physically suppressed by off-axis holography⁵, where the twin images are separated in Fourier space by introducing a small angle in between the reference beam and the object beam. Off-axis digital holography allows the twin image to be filtered out numerically, but this approach can result in sacrificing the space bandwidth product of the system. To overcome the twin image problem, another effective approach is to take multiple measurements, introducing variations in the imaging distance⁶,

illumination wavelength⁷, probe position⁸, modulation pattern⁹, and illumination angle¹⁰. However, the high imaging performance of these approaches often comes at the expense of a lower temporal resolution and sophisticated complex optical system. There is growing interest in developing non-interferometric, single-shot digital holography techniques towards compact systems for quantitative phase imaging (QPI).

Now, writing in an issue of *Light: Advanced Manufacturing*, Yunhui Gao and Liangcai Cao from Tsinghua University report a novel computational framework that achieves quantitative phase reconstruction from a single inline hologram¹¹.

Retrieving the optical phase and amplitude from a diffraction pattern alone has been a long-standing problem. Previously, researchers proposed exploiting the physical knowledge of the wavefield as a simple yet efficient constraint to suppress the twin image¹². Later on, with the advent of compressive sensing and deep learning, more advanced image priors based on the regularization techniques have also been explored in the context of phase retrieval^{13–15}.

However, both of these methods have been studied separately and feature their unique advantages. In this work, Gao et al. proposed an inverse problem approach that encapsulates both physical constraints and sparsity priors within a unified framework. Specifically, the well-known absorption and support constraints, which enforce the wavefield to satisfy the underlying physics, are introduced. Meanwhile, a total variation function is used as a

Correspondence: Juergen W. Czarske (juergen.czarske@tu-dresden.de)

¹Competence Center for Biomedical Computational Laser Systems (BIOLAS), TU Dresden, Dresden, Germany

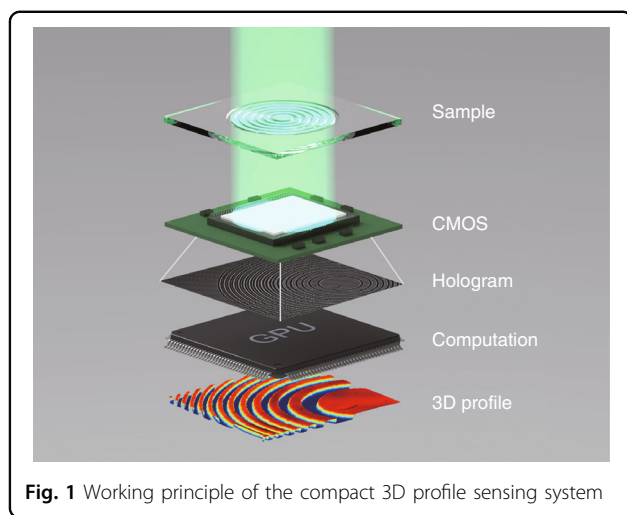
²Laboratory of Measurement and Sensor System Technique (MST), TU Dresden, Helmholtzstrasse 18, 01069 Dresden, Germany

Full list of author information is available at the end of the article

© The Author(s) 2023



Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.



sparsity-promoting regularizer to characterize the piecewise smoothness of the samples. Combining the two leads to a constrained complex total variation (CCTV) model, which can be solved by an accelerated proximal gradient algorithm with an efficient denoiser.

The lensless hologram is recorded directly by an imaging sensor (CMOS) without the need for lenses, enabling an ultra-compact system. Powered by the novel computational framework reported in ref. ¹¹, this system is capable of calculating accurate 3D profiles with nanoscale resolution. Based on a simple lensless system demonstrated in Fig. 1, the authors experimentally demonstrated the QPI capability of the CCTV model on various samples, ranging from biological tissue slides such as muscle tissue to fabricated transparent phase plates. The imaging accuracy has also been quantified by imaging standard amplitude and phase test targets, and the results show good consistency with the ground-truth data. Comparative experiments show that using sparsity regularization can effectively suppress the twin image, while the physical constraints can help further accelerate the algorithm and enhance overall fidelity. Another important insight gained through this work is the convergence behavior of the compressive phase retrieval algorithm. Based on the geometrical properties of the inverse problem, the authors established a general convergence theory that ensures stable convergence of the algorithm with pre-specified parameters. This implies that the proposed algorithm is essentially different from most heuristic phase retrieval algorithms with theoretically tractable algorithmic behaviors. To facilitate further studies, the authors have published open source code and experimental data along with the paper¹⁶. They also elaborate on the parameter selection rules, providing guideline for fast and easy implementation by practitioners of various backgrounds.

The compressive phase retrieval framework proposed in this work has the potential to inspire both theoretical and empirical studies in the future. Despite the iterative reconstruction process, the algorithm allows highly parallel computation and can be accelerated by orders of magnitude with the help of graphical processing units. The computational approach presented in this paper can be readily applied to a wide range of fields, including coherent diffraction imaging¹⁷, optical diffraction tomography^{18,19}, holographic endoscopy^{6,20}, holographic optical manipulation^{21,22}, and biomaterial characterization²³.

Author details

¹Competence Center for Biomedical Computational Laser Systems (BIOLAS), TU Dresden, Dresden, Germany. ²Laboratory of Measurement and Sensor System Technique (MST), TU Dresden, Helmholtzstrasse 18, 01069 Dresden, Germany. ³Cluster of Excellence Physics of Life, TU Dresden, Dresden, Germany. ⁴Institute of Applied Physics, TU Dresden, Dresden, Germany

Published online: 17 May 2023

References

- Javidi, B. et al. Roadmap on digital holography [invited]. *Opt. Express* **29**, 35078–35118 (2021).
- Rothe, S. et al. Securing data in multimode fibers by exploiting mode-dependent light propagation effects. *Research* **6**, 0065, <https://doi.org/10.34133/research.0065> (2023).
- Park, Y., Depeursinge, C. & Popescu, G. Quantitative phase imaging in biomedicine. *Nat. Photonics* **12**, 578–589 (2018).
- Stoykova, E., Kang, H. & Park, J. Twin-image problem in digital holography-a survey (invited paper). *Chin. Opt. Lett.* **12**, 060013 (2014).
- Zhang, J. W. et al. A review of common-path off-axis digital holography: towards high stable optical instrument manufacturing. *Light Adv. Manuf.* **2**, 333–349 (2021).
- Sun, J. W. et al. Quantitative phase imaging through an ultra-thin lensless fiber endoscope. *Light Sci. Appl.* **11**, 204 (2022).
- Bao, P. et al. Phase retrieval using multiple illumination wavelengths. *Opt. Lett.* **33**, 309–311 (2008).
- Faulkner, H. M. L. & Rodenburg, J. M. Movable aperture lensless transmission microscopy: a novel phase retrieval algorithm. *Phys. Rev. Lett.* **93**, 023903 (2004).
- Wu, Y. C., Sharma, M. K. & Veeraraghavan, A. WISH: wavefront imaging sensor with high resolution. *Light Sci. Appl.* **8**, 44 (2019).
- Zheng, G. A., Horstmeyer, R. & Yang, C. Wide-field, high-resolution Fourier ptychographic microscopy. *Nat. Photonics* **7**, 739–745 (2013).
- Gao, Y. H. & Cao, L. C. Iterative projection meets sparsity regularization: towards practical single-shot quantitative phase imaging with in-line holography. *Light Adv. Manuf.* **4**, 6 (2023).
- Latychevskaia, T. & Fink, H. W. Solution to the twin image problem in holography. *Phys. Rev. Lett.* **98**, 233901 (2007).
- Chang, X. Y., Bian, L. H. & Zhang, J. Large-scale phase retrieval. *eLight* **1**, 4 (2021).
- Zhang, W. H. et al. Twin-image-free holography: a compressive sensing approach. *Phys. Rev. Lett.* **121**, 093902 (2018).
- Riverson, Y. et al. Phase recovery and holographic image reconstruction using deep learning in neural networks. *Light Sci. Appl.* **7**, 17141 (2018).
- Gao, Y. H. & Cao, L. C. Compressive phase retrieval via constrained complex total variation regularization (CCTV). *GitHub Repository*. <https://github.com/THUHoldLab/CCTV-phase-retrieval> (2023).
- Miao, J. W. et al. Extending the methodology of X-ray crystallography to allow imaging of micrometre-sized non-crystalline specimens. *Nature* **400**, 342–344 (1999).
- Merola, F. et al. Tomographic flow cytometry by digital holography. *Light Sci. Appl.* **6**, e16241 (2017).

19. Li, J. J. et al. Transport of intensity diffraction tomography with non-interferometric synthetic aperture for three-dimensional label-free microscopy. *Light Sci. Appl.* **11**, 154 (2022).
20. Kuszmierz, R. et al. Ultra-thin 3D lensless fiber endoscopy using diffractive optical elements and deep neural networks. *Light Adv. Manuf.* **2**, 415–424 (2021).
21. Grier, D. G. A revolution in optical manipulation. *Nature* **424**, 810–816 (2003).
22. Sun, J. W. et al. Rapid computational cell-rotation around arbitrary axes in 3D with multi-core fiber. *Biomed. Opt. Express* **12**, 3423–3437 (2021).
23. Koukourakis, N. et al. Investigation of human organoid retina with digital holographic transmission matrix measurements. *Light Adv. Manuf.* **3**, 211–225 (2022).