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Deep learning enabled single-shot absolute phase recovery in high-speed composite fringe pattern profilometry of separated objects

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A recent article in the *Opto-Electronic Advances* (OEA) journal from Prof. Qian Chen and Prof. Chao Zuo's group introduced a new and efficient 3D imaging system that captures high-speed images using deep learning-enabled fringe projection profilometry (FPP). In this News & Views article, we explore potential avenues for future advancements, including expanding the measurement range through an extended number-theoretical approach, enhancing quality through the incorporation of horizontal fringes, and integrating data from other modalities to broaden the system's applications.

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High-speed and high-precision 3D imaging has become a crucial aspect of numerous scientific and industrial applications[1,2]. From robotics and autonomous navigation to biomedical imaging and cultural heritage preservation, the demand for accurate non-contact and real-time measurements of 3D surface geometry continues to grow. Structured light (SL) based 3D imaging techniques[3,4] have already proven their great usefulness and capability in meeting these demands. However, traditional SL approaches often require multiple frames[5,6] to achieve high-resolution reconstructions, leading to longer acquisition times and potential motion artifacts.

Nevertheless, high-precision 3D reconstruction using only one single pattern has been the ultimate goal of structured light 3D imaging in perpetual pursuit. Fourier transform profilometry (FTP)[7], in which the wrapped phase is decoded by Fourier filtering in the fringe pattern spatial frequency domain, enables to demodulate the phase from a single fringe pattern. However, the FTP technique limited to measuring smooth surfaces with limited height variations. In addition, the wrapped phase retrieved by FTP suffers from periodic ambiguity, which typically requires multi-frequency temporal phase unwrapping methods to unwrap and obtain the continuous, absolute phase distribution[8]. Spatial carrier phase shifting methods were also proposed, with similar single-shot limitations[9].

To solve the phase ambiguity problem, Takeda et al.[10] introduced frequency multiplexing (FM) to fringe projection profilometry[1–4] to encode two fringe patterns with different spatial carriers into a single snapshot measurement which can be demodulated from the FM composite fringe to remove the periodic phase ambiguity. Alternatively, Zhang et al.[11] proposed the color frequency multiplexing SL method, in which three sinusoidal fringe patterns with different frequencies are encoded into the red, green and blue (RGB) channels of a color image and three wrapped phases with different

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frequencies can be demodulated from the RGB channels of the captured image. However, as derivatives of FTP, these FM techniques achieved limited success for measuring complex surfaces due to the unavoidable frequency overlapping, spectrum leakage, and channel crosstalk.

New concept in FPP based SL considers implementation of deep learning based frameworks to solve intensity-phase domain transition problem[12–16]. It is based on fringe pattern analysis via especially tailored convolutional neural networks. Phase, although the most important, is one of the parameters that describe and thus can be demodulated from a fringe pattern, alongside with fringe pattern density[17], orientation[18] and background[19,20]. In the recent work[21] entitled "Deep-learning-enabled dual-frequency composite fringe projection profilometry for single-shot absolute 3D shape measurement" published in *Opto-Electronic Advances* (DOI: 10.29026/oea.2022.210021), Prof. Qian Chen and Chao Zuo's group, among main actors in the DL-based SL field, proposed a novel single-shot high-precision 3D imaging method called deep learning-enabled composite fringe projection profilometry (DCFPP) technique, which showcases how deep learning can effectively assist in recovering the absolute phase, thereby enabling precise 3D shape reconstruction from a single frequency-multiplexed fringe image of intricate or isolated objects. This article was selected as the back cover paper of Volume 5, Issue 5 of OEA in 2022 (Fig. 1). Diverging from conventional end-to-end network architectures[16,22], which often exhibit poor accuracy in directly predicting absolute phase or depth from images[12], this research introduces a novel approach. It leverages a dual-frequency compound fringe pattern as the sole input to the network and modifies the output to three components encompassing the wrapped phase arctangent function numerator and denominator terms and the absolute phase map. This work opens new avenues for single-shot, instantaneous 3D shape measurement of discontinuous and/or mutually isolated objects in fast motion.

In comparison to the traditional Fourier transform method, the presented approach mitigates the reduced 3D measurement accuracy caused by spectrum aliasing resulting from generally low spatial frequency of the projected double-frequency pattern. The proposed method achieves performance similar to that of the traditional 12-step phase-shifting method, which is a remarkable result for a single-shot approach. The study demonstrates the efficacy of deep learning in synthesizing both temporal and spatial information, effectively addressing the spectrum-aliasing problem. The article concludes that this approach overcomes the limitations of traditional multi-frequency composite methods and single end-to-end deep learning networks. The utilization of two joined networks proves advantageous as it decomposes the problem into two lines, aligning with the inherent working principle of networks that decompose problems into subsets of convolutional layers.

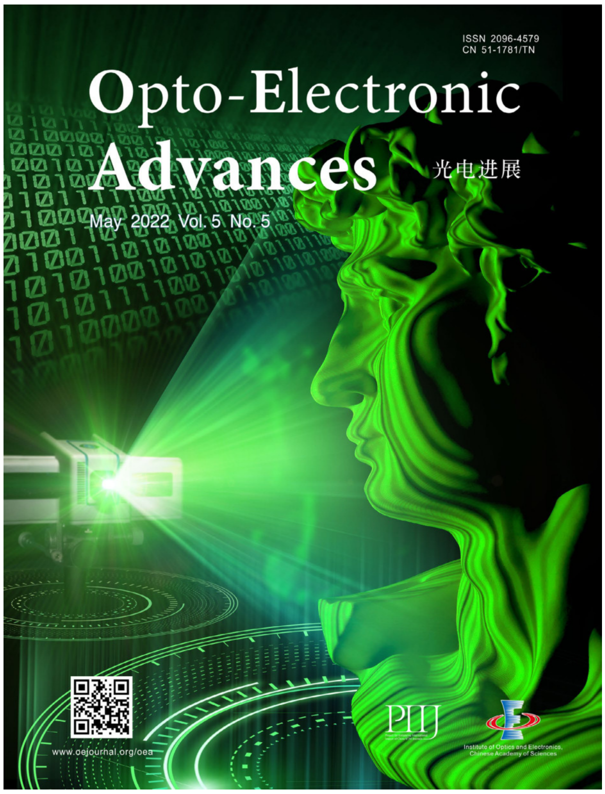

Fig. 1 | Back cover of Volume 5, Issue 5 of OEA in 2022.

However, obtaining high-quality absolute phase information remains challenging due to variations in reflectance, shadows, and high directional gradients in shape. Also, the depth of a measured 3D scene (a measurement range) is limited. The authors emphasize their plans to explore advanced network structures and integrate more suitable physical models into deep learning networks to achieve higher speed, accuracy, and robustness in 3D shape measurement using fewer neural networks or in an end-to-end manner. These AI based enhancements can be assisted by modification of the measurement scenario followed by the proposed DCFPP processing scheme. In Fig. 2 we present two possible avenues for future research. The first scenario can be utilized

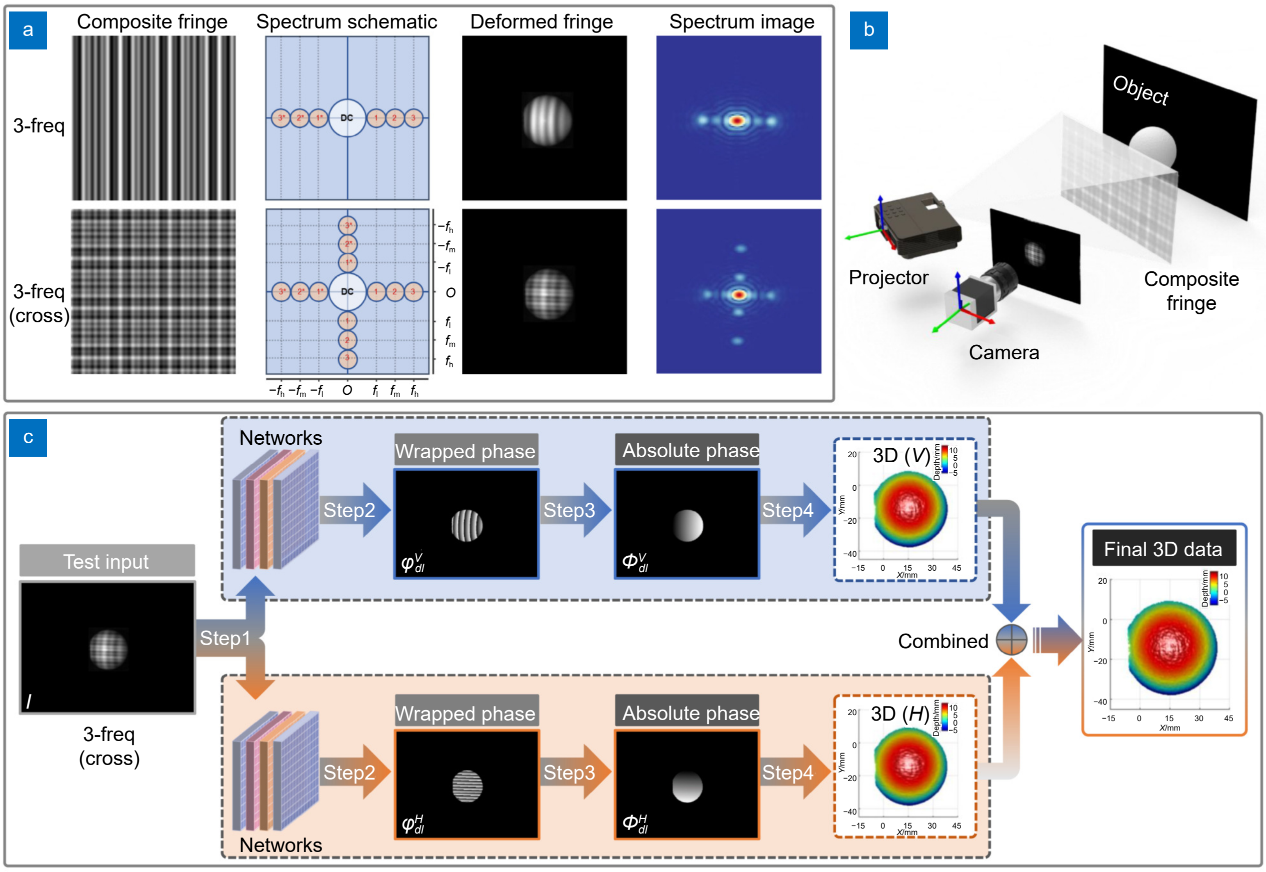

Fig. 2 | Possible future extension of the proposed DCFPP technique: (**a**) the example triple-frequency projected vertical and cross fringe patterns and their spectra, (**b**) the hardware system and (**c**) the enhanced shape reconstruction using cross fringe pattern and two channel reconstructions for vertical and horizontal composite fringe patterns.

when the extension of the measurement range is required. In such a case third or additional wavelengths (fringe pattern frequencies) can be added to project more complex composite fringe pattern (Fig. 2(a, b)) and follow a similar framework as proposed in the Gushov-Solodkin algorithm[23]. In this way the measurement range W is expanded from $LCM(\lambda_h;\ \lambda_l) \geq W$ for two wavelength scheme up to $LCM(\lambda_h;\ \lambda_m;\ \lambda_l) \geq W_{ext}$ for three wavelength scheme, where LCM represents the least common multiple function. The second proposed modification relies on projection a cross fringe composite pattern, namely both vertical and horizontal (or generally inclined with a given angle) fringe families followed by utilizing of the proposed DCFPP processing scheme separately for the information extracted from vertical and horizontal fringes and finally merging the reconstructed phases (Fig. 2(c)).

Such measurement and processing scenario could be investigated to minimize directional errors including reduction of the influence of variations of reflectance and occurrence of shadows in an object.

Another promising avenue for future research involves merging information from other modalities, such as digital image correlation, to enable dynamic 3D shape and displacement mapping[24], potentially advancing the fields of experimental mechanics and structural integrity.

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