Phase retrieval from multiple binary masks generated speckle patterns

Gong, Hai; Pozzi, Paolo; Soloviev, Oleg; Verhaegen, Michel; Vdovine, Gleb

DOI
10.1117/12.2228297

Publication date
2016

Document Version
Final published version

Published in
Proceedings of SPIE

Citation (APA)
Gong, H., Pozzi, P., Soloviev, O., Verhaegen, M., & Vdovine, G. (2016). Phase retrieval from multiple binary masks generated speckle patterns. In F. Berghmans, & A. G. Mignani (Eds.), *Proceedings of SPIE: Optical Sensing and Detection IV* (Vol. 9899). Article 98992N (Proceedings of SPIE; Vol. 9899). SPIE. https://doi.org/10.1117/12.2228297

Phase retrieval from multiple binary masks generated speckle patterns

Hai Gong[*a], Paolo Pozzi[a], Oleg Soloviev [a,b], Michel Verhaegen[a] & Gleb Vdovin [a,b,c]
[a] DCSC, TU Delft, 2628 CD, Delft, The Netherlands; [b] Flexible Optical BV, Polakweg 10-11, 2288 GG Rijswijk, the Netherlands; [c] ITMO University, Kronverksky 49, 197101 St Petersburg, Russia

ABSTRACT

We present a reference-less and time-multiplexing phase retrieval method by making use of the digital micromirror device (DMD). In this method, the DMD functions not only as a flexible binary mask which modulates the optical field, but also as a sampling mask for measuring corresponding phases, which makes the whole setup simple and robust. The DMD reflection forms a sparse intensity mask in the pupil which produces speckle pattern after propagation. With the recorded intensity on the camera and the binary pattern on the DMD, the phase in all the 'on' pixels can be reconstructed at once by solving inverse problems with iterative methods, for instance using Gerchberg-Saxton algorithm. Then the phase of the whole pupil can be reconstructed from a series of binary patterns and speckle patterns. Numerical experiments show the feasibility of this phase retrieval method and the importance of sparse binary masks in the improving of convergence speed.

Keywords: Phase retrieval, adaptive optics, digital micromirror device, inverse problems

1. INTRODUCTION

Phase retrieval is a crucial problem which arises in adaptive optics, digital holography, coherent imaging, phase contrast imaging, and many other applications.[1–3] Holographic based methods, as a main approach to phase retrieval, require a reference beam to be present in the optical setup. They are generally still difficult to implement in practice.[4] Reconstruction of the phase from the diffracted field intensity by solving inverse problems is actively researched.[5,6] Generally these inversed problems are ill-posed, additional information or constrains are necessarily required. Taking multiple diffraction patterns usually enhances the uniqueness. It can be accomplished by modulating the optical field before or after the sample. Many multiple structured illumination approaches, including varying masks, gratings, or the axis position of the sample, are reported.[7,8] However, it is difficult to fabricate masks with high spatial resolution with required structures. Changing the illumination conditions usually needs complex setups.[9]

In this paper, we present an alternative reference-less and time-multiplexing phase retrieval method by making use of the digital micromirror device (DMD). In this method, the DMD functions not only as a flexible binary mask which modulates the optical field, but also as a sampling mask for measuring corresponding phases, which makes the whole setup simple and robust. The DMD reflection forms a sparse intensity mask in the pupil which produces speckle pattern after propagation. With the recorded intensity on the camera and the binary DMD pattern, the phase in all the 'on' pixels can be reconstructed at once by solving inverse problems with iterative methods, for instance using Gerchberg-Saxton algorithm. Then the phase of the whole pupil can be reconstructed from a series of binary patterns and speckle patterns.

2. PRINCIPLES

A digital micromirror device (DMD) is a bidimensional array of thousands of individually switchable micromirrors. It was initially developed by Texas Instrument for image projection. However, due to its excellent spatial light modulation property, emerging new applications are being developed.[10] In our method, the DMD is used to project binary patterns as a method to sample the optical field.

*hgong@tudelft.nl; phone 31 015-2785610; fax 31 015-2786679; www.dcsc.tudelft.nl

Optical Sensing and Detection IV, edited by Francis Berghmans, Anna G. Mignani, Proc. of SPIE Vol. 9899, 98992N · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2228297

The basic principle of phase retrieval is explained in Figure 1. The surface of DMD is illuminated by coherent laser light. The incident light is aberrated by a transmissive phase object. A DMD and a camera are positioned at the back focal plane and front focal plane of a converging lens respectively. The micromirrors of the DMD are randomly switched on to form n frames of binary masks $M_i(\mathrm{i}=1,2,...,\mathrm{n})$. With all these masks, the whole DMD plane will be sampled. Assuming the optical field at the DMD plane is U_{back}, then we have can describe this relation as

$$U_{back}=\sum_{i=1}^{n} M_i U_{back}. \tag{1}$$

In the wave optics, a converging lens performs two-dimensional Fourier transformations. The optical field in the DMD plane and the field in the camera plane U_{front} are related by equation (2).

$$U_{front}(x,y)=\frac{1}{j\lambda F}\iint dx'dy'U_{back}(x',y')e^{-\frac{2\pi j(xx'+yy')}{\lambda F}}=\frac{1}{j\lambda F}\hat{U}_{back}(\frac{x}{\lambda F},\frac{x}{\lambda F}), \tag{2}$$

where F is the focal length of the converging lens, λ is the wavelength, $\hat{U}_{back}$ denotes the Fourier transform of U_{back}. When a binary mask M_i is used to modulate intensity in the plane U_{back}, a speckle pattern I^i_{front} propagated from $I^i_{back}=\left|M_i U_{back}\right|^2$ can be registered by the camera. This speckle pattern contains the information of the complex field of the DMD plane which can be reconstructed by solving inverse problems.

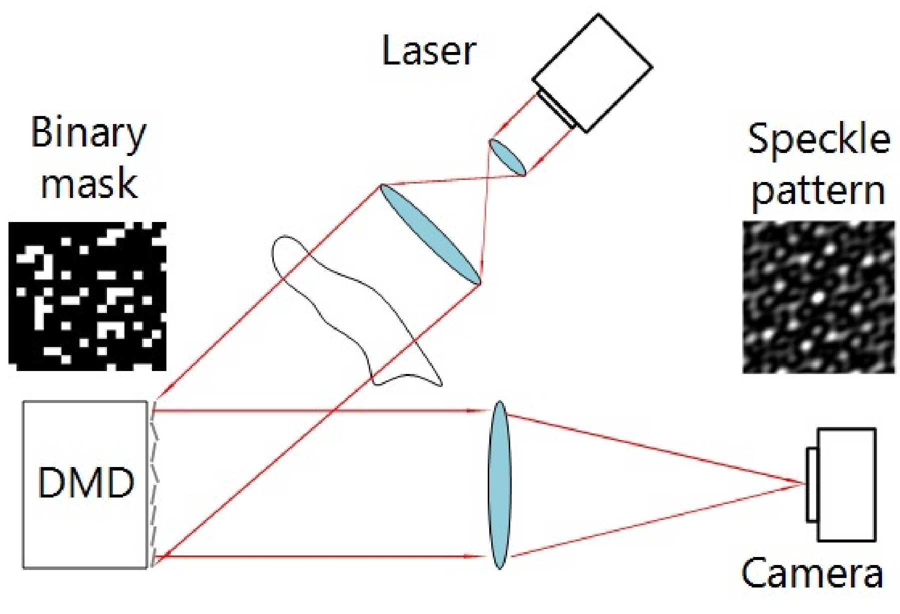

Figure 1 Optical set up for phase retrieval based on the DMD generated speckle patterns

Iteration methods, for instance the Gerchberg-Saxton algorithm, can be used to reconstruct the optical field. The Gerchberg-Saxton algorithm is a classical and stable method most used since 1972.[11] It is based on the iterative calculation of the forward propagation and back propagation, which means Fourier transform and inverse Fourier transform in this case, as described below (see Figure 2 for details).

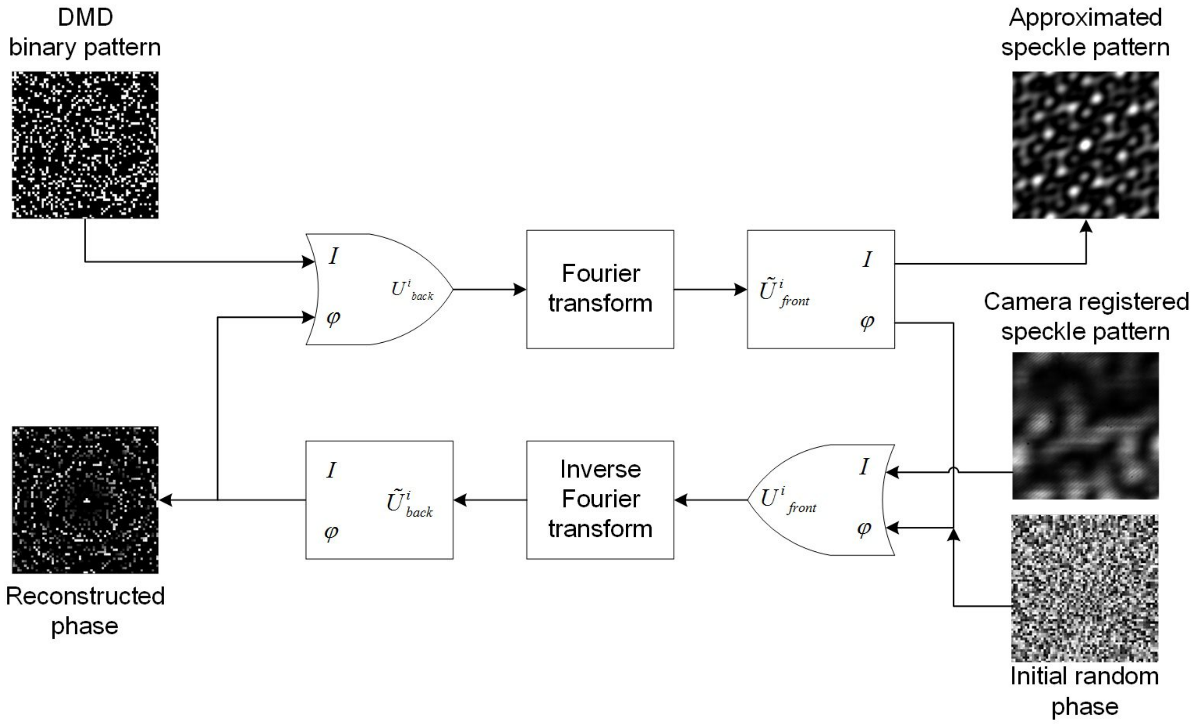

Figure 2 Gerchberg-Saxton algorithm for phase retrieval

We consider the intensity of the DMD plane is known as the binary pattern M_i . In order to retrieve the phase at the DMD plane, the algorithm start with the speckle distribution with a random phase at the camera plane. Then the inverse Fourier transform of the field in the front focal plane U^i_{front} is computed, obtaining the optical field in the back focal plane $\tilde{U}^i_{back}$, with an intensity distribution different from the binary pattern. The phase distribution is conserved, while the intensity distribution is substituted with the known binary pattern. This new field is Fourier transformed, obtaining a pattern $\left|\tilde{U}^i_{front}\right|^2$ at the front focal plane which is similar to the registered speckle pattern. The phase distribution of this pattern is kept, while the intensity is replace with the registered one. Then the inverse Fourier transform is computed again, starting a new iteration cycle. With multiple iterations, the algorithm converges to the exact distribution of the speckle pattern, which contains the right phase of the 'on' pixels of DMD.

All the pixels will be randomly switched 'on' only once during all the frames. The corresponding phases will be registered and combined together with the help of a shared reference, as shown in Figure 3. For instance, a single DMD pixel shared by all frames can be used as a reference to integrate all the phase layers. There is no need of extra setups to create a reference.

Multiple binary patterns are used as randomness and sparsity in the intensity pattern leads to a quick convergence in the iterative method. Such effect will be investigated in the following numerical experiments.

3. RESULTS

Based on the setup in Figure 1, we built a numerical propagation model to validate the feasibility of this method. In order to investigate the effect of sparsity of given binary patterns, the convergence speed is compared in experiments in different frame numbers (1 frames, 5 frames, 20 frames and 40 frames), see Figure 4. The whole dimension of the field is 512x512. The size of DMD is set to be 64x64. A defocus aberration has been applied in the DMD plane.

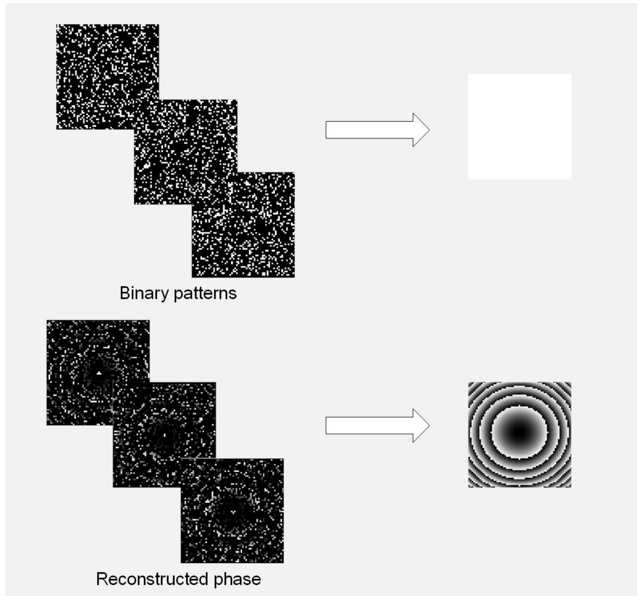

Figure 3 Phase retrieval with multiple binary masks

For a given total number of frames n, there are $4096/n$ micromirrors in the 'on' state in each frame. We reconstructed the phase for each of the frames using Gerchberg-Saxton algorithm. The variances between the given aberration and the reconstructed phase in each cycle have been calculated for the first 200 iterations.

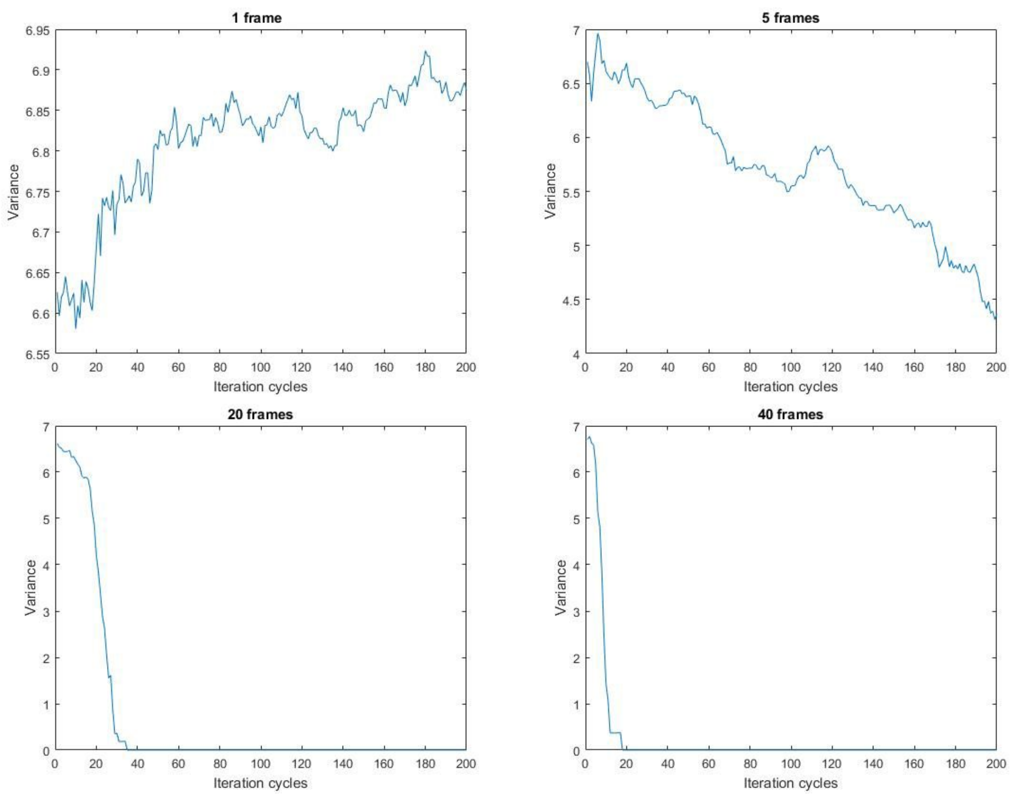

Figure 4 Comparison of the converging speed in different number of frames.

The effectiveness of the proposed method depends strongly on the total number of frames. When there is just one frame to reconstruct the whole pupil, which means all the DMD pixels are switched on at once, the Gerchberg-Saxton algorithm cannot converge to a stable result. With a total of 5 frames, the first 200 iterations shown a trend of convergence. Yet the phase was still not close to the given value. The converging speed increase dramatically with increase of the total number of frame. Less than 40 iteration cycles are needed to converge for n=20, when 5% of the pixels are turned on. The needed amount of iterations is reduced with the increase of n, and thus the increase of sparsity of the DMD patterns. Though the exact number of iterations is changing with different initial guess, this trend reveals that the condition of sparse sampled input intensity is very important to the success of phase retrieval.

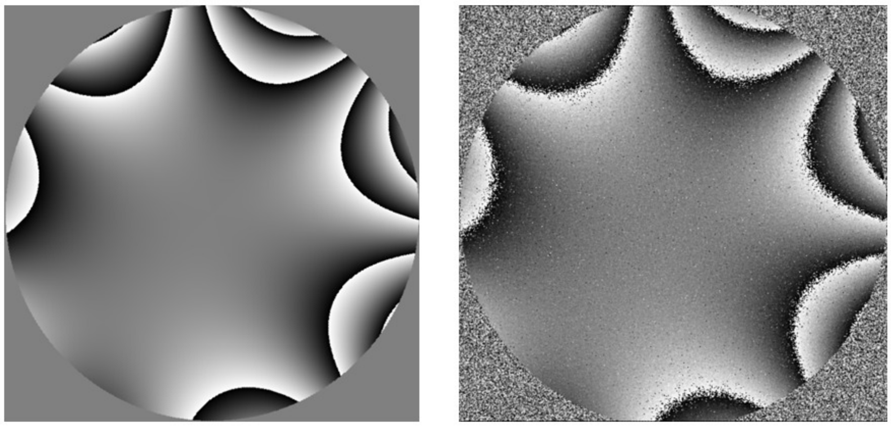

Figure 5 Original phase (left, generated by a sum of Zernike polynomial up to the third order) and phase reconstruction from 50 frames.

Adapting the parameters in the numerical model to our own experimental setups, we demonstrated the full reconstruction of the phase in DMD pupil formed by 304x342 pixels from only 50 frames. Each of the frame was created with 2% of the pixels randomly turned on. In the Fourier plane, every frame generated a single intensity pattern, limited to 255 scales of gray, to represent an 8 bit camera image. The center pixel was designated as a reference which was common between all the frames. The simulation yielded the phase reconstruction of an introduced low-order aberration with ten iterations used in the Gerchberg-Saxton algorithm for each frame.

4. CONCLUSIONS AND OUTLOOKS

We demonstrated the feasibility of phase reconstruction by solving inverse problem from multiple speckle patterns produced by binary masks generated with DMD. The quick convergence in iterative method is conditioned by the randomness and sparsity of the intensity carrier in the DMD pupil.

The experimental implementation of this method is currently in progress. Due to the noise in the real circumstance, more iterations are required. In practice, the propagation model in the iterative algorithm should consider the misalignment and aberrations of the system as well as the computation time in further. In addition, the optimal choice of common reference pixels is also expected to make contribution to reduce the noise.

REFERENCES

[1] Shechtman, Y., Eldar, Y. C., Cohen, O., Chapman, H. N., Miao, J.., Segev, M., “Phase Retrieval with Application to Optical Imaging,” Signal Process. Mag.(April 2015), 1–25 (2014).

[2] Gonsalves, R. A., “Phase retrieval and diversity in adaptive optics,” Opt. Eng. **21**, 829 (1982).

[3] Vdovin, G., Gong, H., Soloviev, O., Pozzi, P.., Verhaegen, M., "Lensless coherent imaging by sampling of the optical field with digital micromirror device," J. Opt. **17**(12), 122001, IOP Publishing (2015).
[4] Schnars, U., Falldorf, C., Watson, J.., Juptner, W., Digital Holography and Wavefront Sensing.
[5] Candès, E. J., Li, X.., Soltanollotabi, M., "Phase Retrieval from Coded Difraction Patterns," Arxiv **2013**, 1–24 (2013).
[6] Candès, E. J., Eldar, Y. C., Strohmer, T.., Voroninski, V., "Phase Retrieval via Matrix Completion," SIAM J. Imaging Sci. **6**(1), 199–225, Society for Industrial and Applied Mathematics (2013).
[7] Miao, J., Charalambous, P., Kirz, J.., Sayre, D., "Extending the methodology of X-ray crystallography to allow imaging of micrometre-sized non-crystalline specimens," Nature **400**(6742), 342–344 (1999).
[8] Miao, J., Ishikawa, T., Robinson, I. K.., Murnane, M. M., "Beyond crystallography: Diffractive imaging using coherent x-ray light sources," Science (80-.). **348**(6234), 249–254 (2015).
[9] Duadi, H., Margalit, O., Mico, V., Rodrigo, J. a., Alieva, T., Garcia, J.., Zalevsky, Z., "Digital holography and phase retrieval," Source Hologr. Res. Technol. InTech (2011).
[10] Dudley, D., Duncan, W. M.., Slaughter, J., "DMD Applications," 14–25 (2003).
[11] Fienup, J. R., "Phase retrieval algorithms: a comparison," Appl. Opt. **21**(15), 2758–2769, OSA (1982).