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Blind speckle illumination for aberration correction

Evolene Premillieu [1], Simon Labouesse [1,2], Kristina Irsch [3], Rafael Piestun [1]

[1] Electrical, Computer and Energy Engineering Department, University of Colorado at Boulder, 425 UCB Boulder CO 80309, USA

[2] Institut Fresnel, Avenue Escadrille Normandie-Niemen 13397 Marseille, France

[3] Institut de la Vision – CNRS, INSERM, Sorbonne University, 17 rue Moreau 75012 Paris, France

Author e-mail address: evolene.premillieu@colorado.edu

Abstract: We propose a computational optical technique based on speckle-pattern illumination of an object and a gradient descent algorithm, enabling aberration correction without requiring the addition of adaptive optics. © 2021 The Authors

1. Introduction

Aberration correction in imaging systems is traditionally done with complex optical designs or adaptive optics. Unfortunately, in some circumstances it is not feasible to use aberration-corrected optics or set up an adaptive-optics sub-system. With the development of computational imaging methods, new algorithms offer solutions for post-processing aberration correction and resolution improvement. Achieving both aberration correction and improved resolution is however not trivial. In recent years, novel algorithms have been developed to recover high-resolution images from a stack of shifted images [1], [2]. The principle consists of scanning a speckle pattern illumination over an area of interest and then recover a high-resolution object from the information encoded in the blurry images. These techniques originated from Blind Structured Illumination Microscopy (Blind SIM) with unknown speckle patterns [3].

Scanning a speckle illumination to acquire fluorescence images works quite well, as demonstrated by Kaikai Guo *et al.* [1]. However, it is not always applicable to any imaging system. He Zhang *et al.* developed a way to perform coherent imaging with improved resolution using scanned speckle illuminations and phase retrieval [2].

Here we propose a new approach using a simple interferometric set-up and requiring no prior knowledge of the system. We aim at correcting for aberrations and improving the resolution using a gradient descent algorithm. We demonstrate the correction of aberrations caused by a prescription lens and reach a resolution limited by the size of the speckles.

2. Methods

An image can be represented mathematically as the convolution between the point spread function of the system and the object times the illumination:

$$y(r, x) = \int h(r - r') \rho(r') E(r' - x) dr'$$

where y is the image, h the point spread function, ρ the object and E the illumination. When shifting the object with respect to the illumination we can recover enough information from the images to find an estimate for all the unknowns. We carry out the reconstruction through a gradient descent algorithm, which is expressed as the minimization problem of the functional J defined as:

$$J = \sum_i \|y^i - h^k \otimes (\rho^k \cdot I_i^k)\|^2$$

We implement an alternating minimization of the criterion. The three gradients are expressed as follows: $\nabla_\rho J = \nabla_\rho \sum_i \|y^i - h^k \otimes (\rho^k \cdot I_i^k)\|^2$, $\nabla_I J = \nabla_I \sum_i \|y^i - h^k \otimes (\rho^k \cdot I_i^k)\|^2$ and $\nabla_h J = \nabla_h \sum_i \|y^i - h^k \otimes (\rho^k \cdot I_i^k)\|^2$.

When the convergence is reached, the algorithm yields an object free of aberrations with a resolution dictated by the speckle size, and estimates of the transfer function of the system, of the illumination and of the actual shift positions. In order to experimentally acquire the data, we build a simple imaging interferometer. We use a He-Ne laser and use a random phase mask on a Spatial Light Modulator (SLM) that we Fourier filter to create the speckle illumination. The object is imaged onto CCD camera. We use motorized linear stages to shift the object with respect to the illumination. The data is acquired for N different steps with $N=5$ on a 30×30 position grid. The step size is set to be smaller than the speckle size ($14.5 \mu\text{m}$ with speckle size $35 \mu\text{m}$, for the data presented).

3. Results

To retrieve an aberration-free, high-resolution image we first generate an estimate of the shifted positions of the object. We also need to generate an initial guess of the object, the illumination and the point spread function of the system to start the gradient descent algorithm.

As an example, we correct the aberrations induced by prescription glasses (spherical aberration of -1 D and astigmatism of 0.25 D) near the Fourier plane of a 4f imaging system. The object is a USAF resolution target, centered on groups 3, 4, 5, 6, and 7. The reconstructed aberration-free object with increased resolution is depicted in Figure 1.

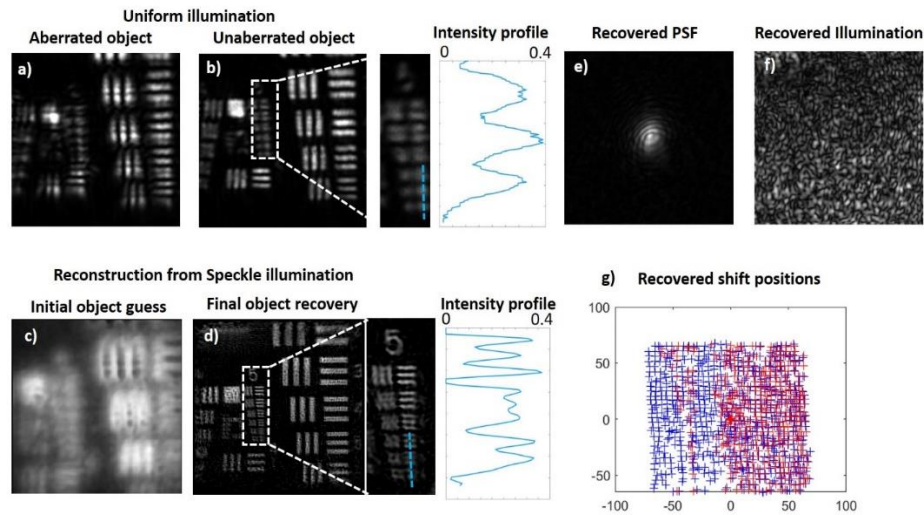


Fig. 1. Experimental results illustrating correction of aberrations from a prescription lens. a) USAF resolution target groups 3, 4, 5, 6, 7 imaged through the aberrated system with uniform illumination. b) USAF resolution target groups 3, 4, 5, 6, 7 imaged through the system with uniform illumination without any aberration induced by the prescription lens. The intensity profile shows that group 5 elements 4, 5, 6 are unresolved. c) Initial guess for the object obtained by averaging images acquired with speckle illumination. d) Reconstruction of the object obtained after 200 iterations of the algorithm. The intensity profile shows that group 5 elements 4 and 5 are resolved, while element 6 remains unresolved. e) Recovered coherent point spread function of the total imaging system composed of 2 imaging lenses and the prescription lens inserted in between. f) Recovered illumination incident on the object. g) Recovered shift positions; the initial estimate of the position grid is shown in blue, while the corrections made by the algorithm are marked in red.

4. Discussion

We introduce a new technique to correct for aberrations in a coherent imaging set-up. A key advantage of our method is that it works in blind conditions where no prior knowledge of the system is required. All that is needed is a speckle illumination and a means to scan the object with respect to the illumination or vice-versa. We anticipate this method could find great use in improving imaging setups as an alternative to adaptive optics.

5. References

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