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Fast localized wavefront correction using area-mapped phase-shift interferometry

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We propose an innovative method for localized wavefront correction based on area-mapped phase-shift (AMPS) interferometry. In this Letter, we present the theory and then experimentally compare it with a previously demonstrated method based on spot-optimized phase-stepping (SOPS) interferometry. We found that AMPS outperforms SOPS interferometry in terms of speed by threefold, although in noisy environments the improvements may be larger. AMPS yielded similar point-spread functions (PSF) as SOPS for moderate system-induced aberrations, but yielded a slightly less ideal PSF for larger aberrations. The method described in this Letter may prove crucial for applications where the phase-stepping solution does not have sufficient speed. © 2011 Optical Society of America

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Optical systems often exhibit aberrations that decrease the amplitude and resolution below that predicted by the idealized point-spread function (PSF). Typically, the first step towards correction involves obtaining a map of the aberrated wavefront. For some applications this is readily accessible and can be sampled using a wavefront sensor (WFS). In many optical systems this is not possible. For example, in multiphoton laser-scanning microscopy (MPLSM) the intensity of the fluorescence signal critically depends on the focal volume [1]. As light travels through an optically inhomogeneous tissue, different rays are delayed by varying amounts, especially when high-numerical aperture objectives are used. To remedy this, nondeterministic algorithms have been used to search the phase-correction space to optimize a certain metric such as fluorescence intensity [2–4]. However, those may fail for high-spatial frequency phase changes since usually only the lower frequencies are probed, due to time and mirror deformability constraints. Other approaches have sampled the wavefront of back-scattered light from the focal region using a WFS [5,6]. The disadvantage is that the back-scattered beam travels out of the tissue and does not fully represent the state at the focal point.

Recently, deterministic methods have been developed for aberration correction. Vellekoop et al. achieved optimal light transport through tissue by changing the phase of each pixel of a spatial light modulator (SLM) to optimize a single pixel on a CCD camera [2]. Čižmár et al. and Ji et al. applied related techniques for optical trapping [8] and MPLSM [9], respectively. Finally, Bowman et al. demonstrated a sensitive method, utilizing an SLM as a Shack–Hartmann WFS to display a grid of focal points to measure and correct the aberrations [10].

In this Letter we analyze the technique proposed by Čižmár et al. and Ji et al. in terms of Fourier optics and demonstrate an innovative and faster method based on the same instrumentation. We emphasize that both methods optimize the focus at a single location. This is important because, when focusing through aberrated media, such as turbid biological samples, different spots may require different corrections [8].

Figure 1 shows the experimental setup (a) and illustrates the division of the SLM into $N^2$ regions (b). Two regions are made active at a time, the scan region (indexed $j$) and the reference region (indexed $k$). Figure 1(c) illustrates the basis of the two techniques. The regions are “activated” by applying a phase gradient to those regions only. The light source is a mode-locked ultrafast Coherent Mira 900 laser, outputting a beam of wavelength 780 nm, which is then filtered and expanded to overfill the SLM.

Figure 1. (Color online) (a) Experimental setup. (b) Definition of scan and reference regions. (c) Illustration of the SOPS and AMPS methods. I: Flat SLM and corresponding zero-order diffraction. II: Scan region activated by applying a phase gradient. Corresponding scan region’s PSF appears on the CCD (circled). III: Reference region activated and an interferogram appears (circled) (Media 1). IV: SOPS (Media 2), V: AMPS (Media 3).
A theoretical framework is now presented to analyze
the method of [8,9] in terms of Fourier optics, upon
which we will base our novel method. The object plane
(SLM) optical field [see Fig. 1(b)] can be written
\[
O_{\phi_k}(x, y) = e^{i2\pi(xT_x+yT_y)} \left[ e^{i\phi_k} \text{rect}\left(\frac{x-x_k}{H}\right) \text{rect}\left(\frac{y-y_k}{H}\right) + e^{i\phi_k} \text{rect}\left(\frac{x-x_k}{H}\right) \text{rect}\left(\frac{y-y_k}{H}\right) \right].
\] (1)

Applying the Fourier transform, the irradiance in the
image plane (on the CCD) is
\[
I(x_i, y_i) = |W(x_i, y_i)|^2 \cdot \left[ 2 + 2 \cos\left(-\frac{2\pi}{\lambda}(D_x x_i + D_y y_i) + \Delta \phi\right) \right].
\] (2)

Here we have defined (for simplification)
\[
W(x_i, y_i) = H^2 \text{sinc}\left(\frac{x_i}{\lambda f} - T_x\right) H \cdot \text{sinc}\left(\frac{y_i}{\lambda f} - T_y\right) H.
\] (3)

where \(H\) is the region height and \(D_x\) and \(D_y\) are the respective horizontal and vertical distances between the scan and reference regions. The function \(W(x_i, y_i)\) represents the window where the interferogram is visible and the phase gradient parameters \(T_x\) and \(T_y\) control its location.

The method that we refer to as spot-optimized phase-
stepping (SOPS) wavefront correction method adds a
phase \(\phi_s\) to the scan region only. This phase is stepped
from 0 to \(2\pi\) in \(M\) steps and the intensity at spot location
\((x_{i0}, y_{i0})\) is recorded. Intensity as a function of scan
phase can then be written as
\[
R_{\text{SOPS}}(\phi_s) = |W(x_{i0}, y_{i0})|^2 \cdot \left[ 2 + 2 \cos\left(-\frac{2\pi}{\lambda}(D_x x_{i0} + D_y y_{i0}) + \Delta \phi + \phi_s\right) \right].
\] (4)

By fitting to the cosine term, the phase offset can be
determined:
\[
(\phi_s)_{\text{fit}} = \phi_{\text{opt}} = \frac{2\pi}{\lambda}(D_x x_{i0} + D_y y_{i0}) - \Delta \phi.
\] (5)

The fit equals the optimal phase \(\phi_{\text{opt}}\) which makes the
scan and reference region arrive in phase and is the condi-
tion for optimal focusing. By iteratively moving the
scan region and finding the phase offset for each region,
the phase map for the whole SLM can be found. One
disadvantage of the SOPS protocol is that it requires a
minimum number, \(M\), of three phase-steps per region
to fully sample the cosine function. However, a higher
number of steps (and thus data points) increases the
accuracy of the phase map and is thus slower.

Instead of stepping the phase of the scan region, we
suggest using the spatially varying phase in the image
plane, which creates the interferogram [Fig. 1(c) V], to
obtain the correction. This method will be referred to
as the area-mapped phase-shift (AMPS) method.

To exploit this information, we combine the spatially
varying phase terms of the cosine in Eq. (2) into a single
phase term as follows:
\[
\phi_a = -\frac{2\pi}{\lambda}(D_x x_i + D_y y_i).
\] (6)

Each pixel within the probe area has an associated
value of \(\phi_a\) and an intensity value. The intensity as a func-
tion of the spatially varying phase \(\phi_a\) can be written as
\[
R_{\text{AMPS}}(\phi_a) = |W(x_i, y_i)|^2[2 + 2 \cos(\Delta \phi + \phi_a)].
\] (7)

By fitting \(R_{\text{AMPS}}(\phi_a)\) to a cosine we find \((\phi_a)_{\text{fit}} = -\Delta \phi\),
and, by comparison with Eq. (5), we have
\[
\phi_{\text{opt}} = \frac{2\pi}{\lambda}(D_x x_{i0} + D_y y_{i0}) + (\phi_a)_{\text{fit}}.
\] (8)

Since all terms in this equation are known, the phase
offset can then be calculated. A correction map for the
whole SLM is obtained by repeating this for all regions.

The run time for both methods is given by
\[
T = MN^2(T_{\text{CCD}} + T_{\text{SLM}} + T_{\text{delays}}) = MN^2T_{\text{iteration}}.
\] (9)

In our setup, the time per iteration is approximately
55 ms (18 Hz), corresponding to 0.88 s, 3.52 s, and 49.5 s
for 4 × 4, 8 × 8, and 30 × 30 region corrections, respec-
tively, for AMPS (\(M = 1\)). The corresponding SOPS cor-
rections require at least three times longer to achieve
optimization.

For validation, AMPS was compared with the SOPS
method. Figure 2 shows results of correcting system
aberrations with increasing number of regions (increas-
ing wavefront detail). Figure 2(a) shows the retrieved
fronts from both methods. Figure 2(b) shows the result-
ing PSFs of our new approach. Figure 2(c) plots the
increase in PSF peak intensity with increasing wave-
front detail. For AMPS and SOPS, the peak intensity
increases were 83% and 82%, respectively. In addition,
the mean intensity of pixels within the full-width half-
maximum (FWHM) is shown and follows the same beha-
vor as the peak intensity. Lastly, in Fig. 2(d), the radial
profiles of the PSFs are shown and compared with that
of the theoretical system. Both methods give nearly
diffraction-limited performance.

In order to evaluate AMPS for correcting larger ab-
errations, an aberrated glass [Fig. 3(a)] was inserted in
front of the focusing lens. Both correction methods were
applied using 900 (30 × 30) regions and Fig. 3(b) shows
the retrieved wavefronts. Figure 3(c) shows the PSFs
for no correction (N/C) (I), AMPS correction (II) and
SOPS correction (III). In addition, the radial profiles are
shown and compared with the idealized system
profile in Fig. 3(d). Without correction, the PSF is
highly diffuse and has weak intensity. Both AMPS and
SOPS provide significant improvements and are compar-
able with the idealized system profile. It is worth noting
that SOPS gave a 23.74% higher peak intensity than AMPS
in this case. In terms of PSF width (or resolution), our
setup was unable to resolve a difference within experi-
mental error, due to the limiting pixel size.

Each correction is localized to a chosen focal location,
which is controlled through the phase gradients \(T_y\) and
When applying a correction and moving the focus away from its nominal location we noted a drop-off in PSF intensity, increasingly with larger displacements. This was more noticeable for larger aberrations, as expected. The AMPS method is very dependent on the validity of our theory, as the correction phase of Eq. (8) includes calculated components. In contrast, the SOPS method is less sensitive as the phase comes directly from fitting. However, this comes at the cost of speed as SOPS is theoretically three times slower and, in practice, may be yet slower for obtaining good fits. For example we used $M = 16$ for our comparisons (sixteenfold slower). We also note that using $M = 3$ resulted in similar PSF improvements. When applying the method in a biological specimen, it is reasonable to expect more noise sources, in which case more data points may be required for fitting.

In summary, we have presented a localized wavefront correction method (AMPS) that performs at least three times faster than the previously published method \cite{8,9}, with similar degree of correction for moderate aberration and only slightly reduced fidelity for larger aberrations. The method is easy to add to a system already implementing SOPS. Then, weighing the importance of accuracy and speed, could reasonably guide the choice of methods for a given experiment.

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