Estimation and Compensation of aberrations in Spatial Light Modulators

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Abstract. The spatial light modulator (SLM) Holoeye LC-R720 is based on LCoS (Liquid Crystal on Silicon) technology. Due to the induced curvatures on the silicon plate by the production process, there are static aberrations in the wave-fronts modified by the SLM. In order to calculate the aberrated wave-front we used phase-shifting interferometry, an optimization algorithm for far field propagation, and the geometric characterization of the focal spot along the caustic. Zernike polynomials were used for expanding and comparing the wave-fronts. The aberration compensation was carried out by displaying the conjugated transmittance on the SLM. The complexity of the experimental setup and the requirements of the digital processing of each estimation method were comparatively analyzed.

1. Introduction

Spatial light modulators (SLMs) are able of modifying the amplitude and phase of an incident wavefront. They are frequently realized by exploiting the birefringence properties of twisted nematic liquid crystals (TNLCD) [1] in both the reflection and the transmission modes. For instance, the Holoeye LC-R720 [2] is a SLM-TNLCD that uses Liquid Crystal on Silicon (LCoS) technology and is operated by reflection. Because of limitations of the LCoS-tech relative to the polishing of the silicon plate that contains the modulator cells [3], static optical aberrations are added to the wavefront. However, the increase in depth of phase modulation and in the response velocity to signals received from video cards of devices based on LCoS-tech has been reported too [4]. Harriman [3] evaluated the aberrations present in the LCoS by applying the phase-shifting interferometric method, and thereafter compensated them by programming the corrections on the same SLM. Otón et al [5] applied this procedure to improve the quality of generated computer holograms (CGHs) displayed on SLM.

In this work, we propose a method to easily determine the aberrations of a Holoeye LC-R720 and to efficiently compensate them, taking into account the changes of the aberrations because of modifications of the strains onto the support structure, for instance due to mounting changes of the device. Specifically, we reinforced the interferometric method for aberration estimation with an iterative optimization algorithm, and the geometric analysis of the focal spots evolution produced by a lens displayed on the SLM. Because the modulation depth of this device under red illumination is limited approximately to $1.2\pi$ rad, only partial compensation is obtained by programming the corrections on it. However, the improvement of the Point Spread Function (PSF) and some CGH reconstructions is notable.
The studied methods are described in Section 2, and obtained wavefronts are analyzed with basis on their Zernike coefficients in Section 3. The experimental and computational requirements of such methods are also discussed in this section. The partial compensation outcomes are shown in Section 4.

2. Description of the studied methods

2.1. Phase – Shifting Interferometry (PSI)

Figure 1 shows the Michelson experimental setup for evaluating the LCoS aberrations with respect to the plane surface of a mobile mirror. Although the SLM is turned-off, the orientations of the linear “polarizer” and “analyzer” allow performing the pure-phase modulation. The displacements of the mobile mirror and the interferogram acquisition were synchronized by a Personal Computer (PC) in a Visual Basic 6 [6] application. Each displacement of the piezo-electric actuator coupled to the mirror is equivalent to 91º.

A set of five acquired interferograms was processed by the Hariharan’s method [7] and the corresponding phase-map was unwrapped in order to obtain the aberrated wavefront produced by the SLM. Figure 2 shows the obtained phase maps a) within a circular aperture over the central zone of the SLM and b) within an elliptical aperture that includes peripheral aberrations. A significant astigmatism is apparent and will be quantified by the Zernike polynomials expansion in Section 3.

2.2. Computational approach to the far-field pattern

This method was proposed by Hart et al [8] in order to calculate a wavefront with optimal fit with the experimental wavefront emerging from the SLM. Therefore, it allows calculating a well-approached far-field intensity pattern to the experimental one. The calculated wavefront is obtained by determining its Zernike coefficients by using the quasi-Newton algorithm of the Optimization Toolbox of MATLAB© [9]. Figure 3a shows the far-field intensity pattern recorded by using an experimental setup that differs from that in Figure 1 in i) the elimination of the path directed toward the mobile mirror and ii) the incorporation of a convergent lens ($f_L=50cm$) in a Fourier transform configuration, i.e. located at distances $f_L$ both behind the SLM and in front of the CCD-camera. In this way, the Fraunhofer diffraction pattern of the wavefront emerging from the SLM is recorded by the CCD camera.
Figure 2. SLM’s phase map using a: a) circular aperture (700x700) on the central zone, and b) an elliptical aperture that includes most the SLM area (1200x700).

Figure 3. a) Measured and b) calculated far-field intensity patterns for the LCoS’s central zone (considering a diameter equal to 10 mm). The length of the red line is 194μm.

Figure 4 schematizes the iterative algorithm that calculates the first fifteen Zernike coefficients \( \{C_k\} \) that assure the best approach to the PSF taken as “merit figure”. The number of iterations is controlled by means of a quality function \( QF \) that quantifies the similarity between the merit figure and the calculated PSF. The best outcome of this procedure is depicted in Figure 3b.

Figure 4. Iterative algorithm for calculating the first fifteen optimal Zernike coefficients \( \{C_k\} \).
2.3. Geometric analysis of focal spots

Figures 2 and 3 reveal that the SLM introduces mainly a significant astigmatism. In order to compensate it adequately, it is useful to analyze the evolution of focal spots along the caustic. To this aim, new variations are introduced in the setup of Figure 1. Specifically, the CCD-camera is fixed at a distance $f \approx 60$ cm from the SLM and the path to the mobile mirror is also canceled. A spherical lens with adjustable focal length between 53.5 and 60 cm is displayed on the SLM, and the intensity pattern produced by changing the focal length is recorded maintaining the camera at the same position. This strategy gives the information we are looking for without the requirement of mobile parts or computers with high specifications. Nevertheless, it requires the previous knowledge of the pure-phase SLM modulation in order to synthesize the optimal diffractive mask.

Figure 8a (Media 1) shows the evolution of the acquired focal spots along the caustic. Each spot was characterized by determining its reduced centered moments of second-order [10], after approaching its morphology to an ellipse, whose parameters $a$, $b$ and $\alpha$ are sketched in Figure 5a. The lengths of the major ($a$) and minor ($b$) axes of the spots are plotted in the Figure 5b. The astigmatism is quantitatively evidenced by comparing of the lengths of the axes $a$ and $b$ for the two axial focal points, placed at the position of the smallest values of the curves. Therefore, the aberration compensation consists in shifting appropriately these curves until placing their minimum values at the same position (i.e. at the same distance $f$ from the SLM. It is performed by manipulating only the second order polynomials of the Zernike pyramid, which are corresponding to astigmatism and field curvature.

3. Comparative analysis of the studied methods

The wavefronts measured by each method were expanded on the first fifteen Zernike polynomials, by using the least-square procedure [11]. The coefficient values plotted in Figure 6 show that the bigger $C_k$ are associated to the second-order aberrations (polynomials 2, 3 and 4). The piston and tilt phases were ignored because they do not affect the quality of the diffraction patterns generated by the SLM.

It is apparent that the geometrical analysis of the spot morphology along the caustic isn’t useful to evaluate and compensate higher-order aberrations. However, we regard it as the best choice to perform the aberration compensation on the SLM for the following reasons:

i) Its efficiency in performing a fast compensation after changing the strains on the SLM.

ii) Its simplicity and consequent versatility in comparison to the other alternatives. Indeed, the interferometric setup requires a Michelson assembly that is impractical in complex arrangements as holographic optical tweezers, for instance. Furthermore, this setup requires an unwrapping phase procedure that increases the complexity and time consume of the numerical calculation. On the other hand, the computational approach to the far-field pattern does not need a special experimental setup, but it is runtime consuming due to the number of iterations performed to replicate the Fraunhofer pattern of the SLM. For example, 67 iterations needed approximately four hours of runtime with a machine equipped with a AMD-Athlon 2.61 GHz processor and 2GB of RAM memory.

iii) Mobile components or further modifications to the experimental setup are not necessary to determine the compensating phase-map, depicted in Figure 7. In addition, the acquired images can be processed without special software or high performance computers.
Figure 5. a) Geometric parameters for the focal spots produced by the lens of variable focal length displayed on the SLM. b) Measured lengths of the axes $a$ (red) and $b$ (green) at $\alpha=35^\circ$ for the lens of variable focal lens.

Figure 6. Comparison of Zernike coefficients for each wave-front obtained with the three methods explained above.
4. Partial compensation outcomes

The compensating phase-map in Figure 7 was added to the lens of variable focal length used for the geometrical analysis of focal spots method. Then, new focal spots were acquired in order to verify the correction. Astigmatism reduction is apparent in Figure 8b (Media 2) that shows the significantly well approach of the PSF to the rotation symmetric merit figure. Nevertheless, the ring structure are split which indicates the presence of a residuary astigmatism. The correction is not complete because of the limitation in phase modulation depth of the used SLM to $1.2\pi$ rad.

Figure 9 illustrates the aberration compensation of the SLM in the reconstruction of the Fresnel hologram of “Felix cat” cartoon [12] a) without and b) with partial astigmatism compensation. The improvement is perceived mainly at the edges of the reconstruction. In order to facilitate the compensation identification, a reticule of squares was added to the same object prior to the reconstruction. Figures 9c and 9d clearly show the aberration compensation that results after adding the compensating phase to the CGH reconstruction.

Figure 8. Spot focal evolution video when the camera is placed 60cm away from the SLM a) without (Video1.avi) and b) with (Video2.avi) aberrations correction. In the modulator was displayed a lens set with focal distance between 53.5 and 60 cm.
Figure 9. Reconstruction of “Felix cat” hologram a) without and b) with partial aberration compensation. The same object with a reticule of squares was reconstructed c) without and d) with the addition of the correcting phase.

5. Conclusions
We characterized the aberrations of the LCoS SLM Holoeye LC-R720 by using three methods: phase-shifting interferometry, a computational estimation of far-field intensity pattern, and the geometrical analysis of focal spots. The Zernike coefficients of the aberration phase-maps obtained by these methods mainly coincide in pointing out a significant astigmatism and field curvature introducing by the SLM. Because of its efficiency, simplicity and rapid response, we regard the last method as the best choice in order to determine the aberrations of this SLM and to compensate them in specific applications, even considering the change of strains on the device.

References
[1] Saleh B. E. A. and Lu K. 1990 *Opt. Eng.* 29 240
[2] *Spatial Light Modulator LC-R 720* (http://www.holoeye.com/spatial_light_modulator_lc_r_720.html)
[3] Harriman J. L, Linnenberger A., and Serati S. 2004 *SPIE Proceedings* 5553 58
[4] Kelly T. and Munch J. 1998 *Opt. Commun.* 156 252
[5] Otón J., Ambs P., Millán M. S. and Pérez-Cabrè E. 2007 *Appl. Opt.* 46 5667
[6] *Visual Basic Developer Center* (http://msdn.microsoft.com/en-us/vbasic)
[7] D. Malacara 2007 *Optical Shop Testing* (New York: John Wiley & Sons)
[8] Hart N. W., Roggemann M. C., Sergeyey A. and Schulz T. J. 2007 *Opt. Eng.* 46 86601
[9] *Optimization Toolbox - MATLAB* (http://www.mathworks.com/products/optimization/)
[10] Castaneda R., Garcia-Sucerquia J. and Brand F. B 2003 *Opt. Commun.* 227 37
[11] D. Malacara, M. Servín, and Z. Malacara 2005 *Interferogram analysis for optical testing* (New Jersey: Taylor & Francis)
[12] *Welcome to Felix the Cat* (http://www.felixthecat.com)