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Phase mask selection in wavefront coding systems: A design approach

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ABSTRACT

A method for optimizing the strength of a parametric phase mask for a wavefront coding imaging system is presented. The method is based on an optimization process that minimizes a proposed merit function. The goal is to achieve modulation transfer function invariance while quantitatively maintaining final image fidelity. A parametric filter that copes with the noise present in the captured images is used to obtain the final images, and this filter is optimized. The whole process results in optimum phase mask strength and optimal parameters for the restoration filter. The results for a particular optical system are presented and tested experimentally in the laboratory. The experimental results show good agreement with the simulations, indicating that the procedure is useful.

1. Introduction

Wavefront coding is based on a combination of digital and optical components in the design of imaging systems. It relies on the optical modification of the transmitted wavefront by means of a phase mask placed at the aperture stop of the system. The design of this phase mask allows image formation that is invariant despite the effects of different optical aberrations [1–4]. Such a modification causes blurring of the images captured by a CCD in the sensor plane. However, these are not the final output of the hybrid system and a postprocessing stage restores the final images. With such a schema, a hybrid design is able to produce imaging systems with improved depth of field (DOF) which means that the system becomes insensitive to defocus aberration to some extent.

Different aspects need to be considered in the design of the hybrid system. There is a trade-off between the degree of invariance achieved and the final image quality resulting from the strength of the phase mask, the noise power and the restoration filter. All of this is dependent on the specific application particulars.

Moreover, the development of combined optical and digital imaging systems together with the use of programmable spatial light modulators (SLMs) that are able to produce tunable wavefront modification has led to the desirability of flexible wavefront coding imaging systems. This means that a strategy is needed not only to design wavefront coding imaging systems but also to incorporate into these systems the possibility of setting the codification according to the requirements of a specific application.

Apart from a phase mask with a cubic profile [1] and its generalization [5], different alternative shapes have been proposed [6–11]. Also, the literature contains different approaches to optimization of the pupil phase modulation aimed at obtaining defocus insensitivity. Dowski [1] and FitzGerrell [2] suggest an analytical framework based on the use of the Ambiguity Function that allows visualization of the properties of a given one-dimensional wavefront coding design. The requirement that the Ambiguity Function be approximately independent of the defocus leads to the cubic phase mask as the optimum shape among monomial-shaped phase masks. Prasad et al. [5] report results for the generalized cubic phase mask, based on other merit criteria. Caron [12] reports an iterative method for optimizing polynomial phase masks (both shape and strength) based on the evaluation of the resultant modulation transfer function (MTF) of the optical system. Other alternatives [13–15] have been reported whose general purpose is to extend the DOF through optimizing the pupil phase modulation, though they are aimed at all-optical imaging systems.

These approaches are all based on evaluation in the intermediate stage, hence they consider only the optical component of the hybrid system. This component is obviously responsible of providing the desired invariance, but limiting evaluation to this stage excludes any effects of the image acquisition and restoration processes. The particular characteristics of them may affect the optimal design of the whole hybrid optical–digital imaging system.

With this in mind, this work proposes a simple and global approach to evaluating the whole hybrid imaging system, in order to aid the design of wavefront coding imaging systems. The goal is to establish a procedure for the selection of a suitable phase mask strength and the filter parameters, given the characteristics of a particular optical system (optical data, noise power of the sensor, and the invariance required). The procedure concludes defining a selection

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table that relates the desired invariance range, the optimum phase mask strength and the corresponding associated restoration filter.

The paper is organized as follows. Section 2 relates the basics of wavefront coding theory. The proposed optimization procedure is presented in Section 3 and optimization results are summarized in Section 4. In Section 5 a second optimization procedure for the restoration stage is proposed. Section 6 shows some experimental results that verify the optimizations. Finally, the conclusions are presented in Section 7.

2. Theoretical background

Image formation by an optical system under incoherent light illumination can be modeled as the combination of its point spread function (PSF) with the scene imaged (assuming a spatially invariant system). The required operation becomes direct multiplication by the optical transfer function (OTF) in the Fourier space, plus the detection pixelation and noise addition,

$$g = s * h + n \longleftrightarrow G = S \cdot H + N \tag{1}$$

where g is the captured image, h is the PSF of the system, s is the pixelated scene that is imaged and n is the noise realization present in the captured image; the capital letters correspond to the discrete Fourier transforms.

For an aberration-free optical system, the presence of a phase mask modifies the pupil wavefront from the diffraction limited field, changing the OTF of the system. For a defocused wavefront coding system, H is

$$H(W_{20},\phi) = R[e^{i\cdot 2\pi\cdot W_{20}(x^2+y^2)} \cdot e^{i\cdot 2\pi\cdot \phi(x,y)} \cdot P(x,y)] \tag{2}$$

where R stands for the autocorrelation operator, W_{20} is the defocus aberration parameter, (x,y) are the pupil coordinates normalized at the pupil aperture, ϕ is the modulation introduced by the phase mask and P is the limitation of the aperture pupil of the system, i.e.,

$$P(x,y) = \begin{cases} 1 & \text{if } (x,y) \text{ is inside the aperture} \\ 0 & \text{if } (x,y) \text{ is outside the aperture} \end{cases} \tag{3}$$

The modulation introduced by a cubic phase mask is expressed as

$$\phi_c(x,y) = \alpha(x^3+y^3) \tag{4}$$

where α determines the strength of the phase mask. Another commonly used mask is the generalized cubic phase mask,

$$\phi_g(x,y) = \alpha(x^3+y^3) + \beta(x^2y+y^2x) \tag{5}$$

where $\beta = -3\alpha$ is usually assumed [5].

The restored scene will be,

$$r = \mathcal{F}^{-1}\{G \cdot F \cdot H_{dl}\} \tag{6}$$

where $\mathcal{F}^{-1}$ stands for inverse Fourier transformation, F is the restoration filter defined in the Fourier space and H_{dl} is the OTF of the system limited by diffraction; i.e.,

$$H_{dl} = R[P(x,y)]. \tag{7}$$

H_{dl} is incorporated in Eq. (6) because the restoration process only aims to recover the optical modification produced by the phase mask. One very basic choice for F is the Wiener filter [16],

$$F = \frac{H_c^*}{H_c^2 + K} \tag{8}$$

where * denotes a complex conjugate, H_c is the OTF restoration-kernel (typically the OTF of the system with aberration centered on the invariance range):

$$H_c(\phi) = R[e^{i\cdot 2\pi\cdot \phi(x,y)} \cdot P(x,y)], \tag{9}$$

and K is the ratio between the noise and the scene power spectra. When the noise and scene power spectra are not known, an adjustable constant k and a frequency-function dependency are considered; namely,

$$K = k(u^2+v^2)^{\omega} \tag{10}$$

where (u, v) are the frequencies in the Fourier plane. When $\omega = 0$, F becomes the parametric Wiener filter. Eq. (10) corresponds to a white noise assumption and a frequency dependency given by the type of scenes to be restored [17,18].

Since defocus aberration is symmetric with respect to the infocus plane, the invariance range will be $[-W_{20}, W_{20}]$, which corresponds to the extended DOF of the imaging system. Thus, the aberration-free OTF of the system will be used in Eq. (8) as the restoration-kernel OTF.

An important drawback of wavefront coding techniques is noise amplification in the images. Since the effect of the phase mask is to broaden the PSF, and hence to reduce the MTF, the noise present in the captured images will undergo the same restoration process and be unavoidably amplified [19].

3. Phase mask strength optimization

Regardless of the shape of its phase mask, a wavefront coding imaging system is expected to reduce image quality but to increase aberration invariance as the strength of the phase mask increases. Thus, as mentioned above, the goal of this work is to obtain the phase mask strength that best suits the trade-off between invariance to defocus and image fidelity. The procedure consists of obtaining the solution by minimizing a given merit function. The merit function proposed is

$$\Psi(W_{20},\phi) = \mathrm{RMS}\{|T(W_{20},\phi)| - |H_{dl}|\} \tag{11}$$

where RMS$\{\cdot\}$ stands for the root mean squared operator and T is the restored OTF of the imaging system. Using Eqs. (2) and (8),

$$T(W_{20},\phi) = H(W_{20},\phi)\frac{H_c^*(\phi)H_{dl}}{|H_c(\phi)|^2 + K} \tag{12}$$

Note the explicit dependency of T on the defocus aberration and on the phase mask profile.

Different remarks can be made concerning the definition in Eq. (11). Firstly, it is implicitly assumed that the intermediate levels of degradation (any amount below that specified by the desired invariance) will also produce an intermediate quality image. This fact is not strictly true, as it is possible that $\Psi(W'_{20},\phi) > \Psi(W_{20},\phi)$ for $W'_{20} < W_{20}$. But in practice, as the phase mask shape is fixed, this is small enough to be neglected, as illustrated in Section 4. Secondly, the merit function directly accounts for both the invariance achieved and the image fidelity since they are compared for the diffraction limited OTF, H_{dl}, instead of the restored OTF with no aberration, $T(0,\phi)$. This penalizes excess codification. Thirdly, the comparison is made once the detection and restoration stages have been performed, and hence accounts for any influence they may have. And finally, it is worth mentioning that since it is based on OTF analysis, it leads to a general design and does not require any particular scene to evaluate the imaging performance (which would influence the evaluation and be vulnerable to PSF shifting or mismatching effects [4]).

Furthermore, note that no noise considerations are taken into account in this merit measure. This is deliberate, since it is assumed that the best noise filtering strategy is inherently incorporated in the restoration filter. Clarifying how this may affect the results is the goal of Section 5.