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Adaptive optics system simulator

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ABSTRACT

In this paper we present the development of a computational tool that simulates the behavior of the basic devices in an adaptive optics system. These elements are a deformable mirror, a Shack-Hartmann wavefront sensor and a basic control system. To represent the wavefront and the deformable mirror surface, Zernike polynomials and Gaussian profiles as influence functions, respectively, were used. The Shack-Hartmann sensor was represented by a lenslet array and the irradiance pattern was obtained using the Fourier Optics theory. The developed programs enable calculation of the reconstruction and influence matrices, as well as estimation of the Zernike coefficients and vector voltages required for the actuators of the deformable mirror. In the programs the user can change the number of lenslets in the Shack Hartmann sensor as well as the number of actuators in the deformable mirror. This simulation system can be used as support tool with a real system or alone to improve the understanding of the elements in the Adaptive Optics system when there is no access to an experimental setup.

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1. Introduction

Adaptive Optics (AO) systems are used to measure and correct wavefront aberrations in real time. AO has its origins in astronomy [1], however nowadays it is used in a broad range of applications, such as military technologies, large transmission capacity communication systems, ophthalmology [2–5], and others.

These systems can be divided in different blocks dependent on each other: (a) a wavefront (WF) detection system, which contains the optical arrangement that allows evaluating the WF. For this purpose usually a Shack Hartmann (SH) sensor is used [6–8]; (b) a control algorithm, usually implemented and processed in a computer. Such control is based on the signals obtained from the SH sensor [9,10]; and (c) a WF correction system, commonly a deformable mirror (DM) [14,15].

The development of such systems involves understanding different concepts in different areas, from optics to electronics at theoretical level and their practical implementation.

Up to our knowledge, it does not exist a computational tool that simulates the behavior of the devices in the AO system, neither the performance of the complete system or that allows the analysis of a specific WF.

Therefore, in this paper a simulation of an AO system, which provides the practical functioning of the most important system devices, is proposed. Particular emphasis was performed on the SH sensor and DM. To achieve this, different programs were developed. These programs allow generating a WF, to obtain the reconstruction matrix based on the Zernike polynomials and calculate the coefficients of such polynomials. After that with the Zernike coefficients, the WF is reconstructed. Next, the program obtains the influence function matrix, which allows calculating the voltage vector for the DM actuators and visualize the deformation adopted by the DM using this vector. Finally, the WF corrected by a simple proportional control system is visualized on the PC screen.

2. Materials and methods

A diagram of a typical AO system with a feedback closed-loop, is shown in Fig. 1. These elements are: (1) the input WF, which is basically, the representation of the image to be measured by the optical arrangement. (2) The SH sensor, is the device that allows evaluating the WF by measuring the slopes of the WF in the directions of x and y axes. (3) The membrane DM is a reflective surface capable of deforming to correct the aberrations of the input WF. (4) The control system allows to calculate correction to be done by the deformable mirror. (5) The WF aberration is the deformation of the input WF when it travels through a turbulent medium. The elements of the Adaptive Optics System Simulator (AOSS) that are simulated are marked with dotted circles in Fig. 1.

For simplicity we will assume that the wavefront covers the entire simulated area of the lenslets in the SH sensor and the actuators of the DM.

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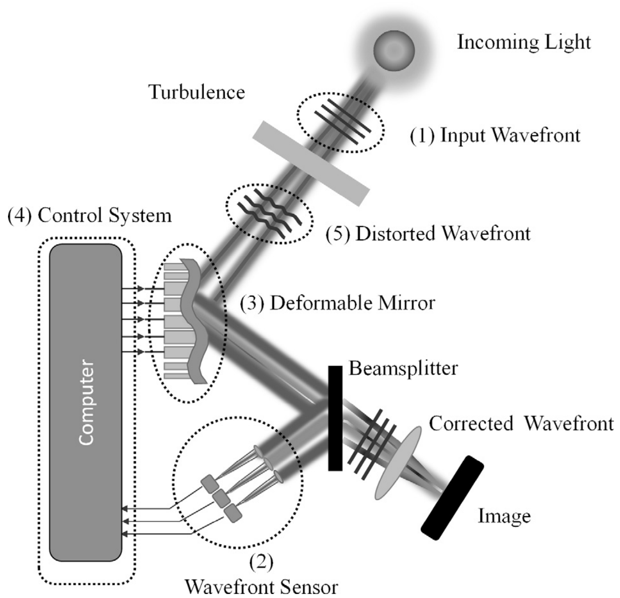

Fig. 1. A diagram of a closed loop adaptive optics system and the elements simulated with the AOSS: (1) Input wavefront. (2) Wavefront sensor: Shack-Hartmann sensor. (3) Wavefront correction device: deformable mirror. (4) Control system (5) Distorted wavefront. Dotted contours indicate elements modelled with the AOSS.

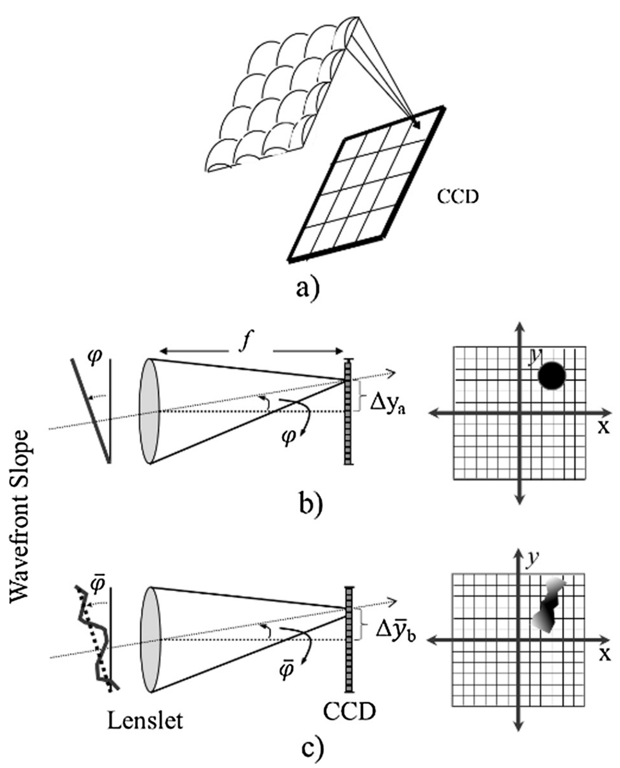

Fig. 2. Analysis of the wavefront with a Shack-Hartamann sensor. (a) The sensor measures the slopes of the WF with the use of a lenslets array. (b) If the portion of the WF on a selected lenslet is plane, a perfect spot is generated at the CCD camera, at the position $\Delta_{x,y}$ in the Cartesian coordinate system centered at the lenslet's optical axis. Spot position is proportional to the wavefront slope. (c) If the portion of the WF is not plane, an irregular spot is generated.

2.1. Modelling of the SH wavefront sensor

The SH sensor is a device consisting of an array of lenslets focused onto a CCD camera. Each lenslet is asocciated with a group of photosensitive elements of the CCD matrix (Fig. 2a). The SH sensor enables the analysis of the wavefront by a measurement of the wavefront slopes in the x and y axes of a cartesian coordinate system associated with the WF detector.

In the original model, the local slope is determined by the position of the spot generated by each lenslet in its respective region on the CCD camera. If the portion of the incident wavefront on the lenslet is tilted, as shown in Fig. 2b, then the spot is shifted on the focal plane away from the optical axis lenslet. The local wavefront slope ($S_{x,y}$) is related to the spot position ($\Delta_{x,y}$) through: $S_{x,y} = \Delta_{x,y}/f$, where f is the focal distance. The maximum slope (S_{max}) which can be unambiguously measured with the sensor, can be approximated by the focal distance and the size of the CCD region corresponding to each lenslet, typically equal to the size of a single lenslet, as: $S_{max} = a/2f$, where a is the size of the lenslet. The maximum slope defines the dynamic range of a SH sensor. In this approximation, we assumed that each lenslet in the array is independent, and the dynamic range was limited just by the focal distance and the lenslet diameter. However, in real systems this not true, since the diffraction effects of each lenslet may affect its neighbors. . A more realistic model is thus required to numerically simulate the wavefront sensor. Such model can be obtained using the Fourier Optics theory.

The model which we adopted in the AOSS uses the Fourier optics methods [11,12] to calculate the diffraction pattern generated by the lenslet array in the CCD plane. With the use of the Fresnel diffraction theory, the complex amplitude, u_f, of the light wave in the CCD plane, can be expressed as [13]:

$$u_f(x_f, y_f) = \frac{1}{j\lambda f}\exp\left(j\frac{k}{2f}(x_f^2 + y_f^2)\right) \times FF\left\{u_0(x,y)\sum_{m=1}^{M}\sum_{n=1}^{N}\exp\left(-j\frac{k}{2f}((x-ma)^2 + (y-nb)^2)\right) \times rect\left(\frac{x-ma}{a}\right)rect\left(\frac{x-nb}{b}\right)\exp\left(j\frac{k}{2f}(x^2+y^2)\right)\right\} \quad (1)$$

where u_f is the wave on the CCD, λ is the WF wavelength, f is the focal length, a, b are the sizes of the square lenslets and $u_0(x,y)$ is the WF near to the plane behind of the SH sensor, x, y and x_f, y_f are the coordinates of the lenslets and focal planes, respectively, and $FF\{\}$ is the two dimensional Fourier transform.

Therefore the irradiance pattern on the CCD is:

$$I(x_f, y_f) = u(x_f, y_f)u^*(x_f, y_f) \quad (2)$$

where $u^*(x_f, y_f)$ is the complex conjugate of $u(x_f, y_f)$. In this case, the irradiance on the CCD is the pattern of the spots generated by the lenslets. The centroid position Δ_x and Δ_y of each spot in each subaperture S can be calculated using the following expressions:

$$\Delta_x = \frac{\iint_s xI(x,y)dxdy}{\iint_s I(x,y)dxdy} \quad (3a)$$

$$\Delta_y = \frac{\iint_s yI(x,y)dxdy}{\iint_s I(x,y)dxdy} \quad (3b)$$

Finally, the slope of the wavefront can be calculated by:

$$S_x = \frac{\partial WF}{\partial x} = \frac{\Delta_x}{f} \quad (4a)$$

$$S_y = \frac{\partial WF}{\partial y} = \frac{\Delta_y}{f} \quad (4b)$$

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