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A new performance metric on sensorless adaptive optics imaging system

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A B S T R A C T

Sensorless adaptive optics (AO) imaging systems have been widely studied in recent years. To reach optimum results, such systems require an efficient performance metric. In this paper, a new performance metric applied to sensorless AO system based on stochastic parallel gradient descent (SPGD) algorithm is presented. This new metric has better performance of stability and correction ability compared with other three performance metrics (i.e. Strehl Ratio, Power-In-Bucket and Image Sharpness), and similar with mean radius (MR) metric but easier to measure by a photo-detector using a mask which can be simply-manufactured. Numerical simulations of AO corrections of various random aberrations are performed. The results show the superiority of the new metric.

1. Introduction

Adaptive optics (AO) has been successfully applied to correct optical aberrations in astronomical imaging [1], vision science [2], microscopy [3], and high-power lasers [4]. In order to correct optical aberrations, it is important to measure the aberrations firstly. In a conventional adaptive optics system, a wavefront sensor such as Shack–Hartmann wavefront sensor is usually employed to measure wavefront aberrations directly, and then a deformable mirror is used to correct the aberrations. Furthermore, a feedback control system is utilized to link these two elements [5]. However, this kind of adaptive optics system is not suitable in some situations where wavefront distortions are difficult to measure directly, such as inertial confinement fusion [6] and microscopy. Fortunately, sensorless AO approaches become an alternative method to correct the aberrations in these situations.

Sensorless AO approaches are generally based on the optimization of some performance metrics that depend on the optical system under consideration. The algorithms for the sensorless correction can be divided into two main classes: the stochastic and the image-based ones. In the stochastic method, the system is optimized starting from a random set and, then, applying an iterative selection of the best solutions. These algorithms have the advantage of not requiring any preliminary information about the system but they take a lot of time for converging. Many algorithms using this approach have been written and exploited successfully in different fields. Among them the most popular are: stochastic parallel gradient descent (SPGD) [7], genetic algorithms [8], simulated annealing [9] and simplex [10].

The SPGD algorithm is a simple and fast method, but the optimization result often falls into the local optimum [9], which depends extremely on the performance metric and starting point of the correction process. In order to decrease the probability of falling into the local optimum, an efficient performance metric is required.

In this paper, we present a new performance metric applied to sensorless AO system. Compared with traditional performance metrics, the new performance metric has better performance of stability and correction ability. Numerical simulations of AO corrections of various random aberrations are performed. The paper is organized as follows: Section 2 introduces sensorless AO system, SPGD algorithm, traditional performance metrics and the new performance metric; numerical simulations results show the superiority of the new performance metric in Section 3; finally, concluding remarks are presented in Section 4.

2. Theory and algorithm

2.1. Description of sensorless AO system

Tthhe schematic diagram of a sensorless AO system is shown in Fig. 1. It includes an imaging system that records intensity

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0030-4026/

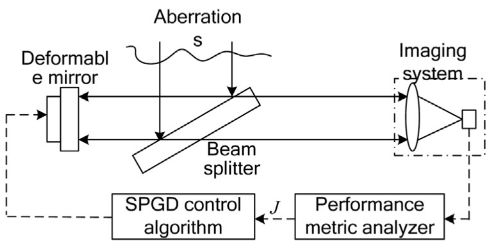

Fig. 1. Schematic diagram of a sensorless AO system.

distribution, an image quality analyzer that calculates the image quality metric and the SPGD algorithm that produces control signals for a 61-element deformable mirror according to changes of metric. The phase compensation $\phi_c(x, y)$, introduced by the deformable mirror, can be combined linearly with influence functions of actuators:

$$\phi_c(x, y) = \sum_{j=1}^{61} u_j S_j(x, y), \tag{1}$$

where $S_j(x, y)$ is the influence function and u_j is the control signal of the jth actuator. On the basis of experimental measurements, we know the actuator influence function of 61-element deformable mirror actuators is approximately Gaussian [11]:

$$S_j(x, y) = \exp\left\{ \ln\omega \left[\frac{\sqrt{(x-x_j)^2 + (y-y_j)^2}}{d_0} \right]^{\alpha} \right\}, \tag{2}$$

where (x_j, y_j) the location of the jth actuator, ω is the coupling value between actuators and is set to 0.08, and α is the Gaussian index and is set to 2. The distance between actuators is d_0 which is about 0.1323 normalized in a unit circle. Fig. 2 gives actuators location distribution of deformable mirror. The circled line in the figure denotes the effective aperture and the layout of all actuators is hexagonal.

2.2. SPGD algorithm

The basis of the SPGD algorithm is the optimization of a performance metric using random perturbations applied to the actuators. In parallel stochastic optimization, small random perturbations $\{+\delta u_j\}$ are first simultaneously applied in parallel to all the N control channels of the system, and the perturbed system performance metric is obtained as

$$\delta J_+ = J(u_1 + \delta u_1, u_2 + \delta u_2, \ldots, u_N + \delta u_N). \tag{3}$$

Then perturbations in the other direction (negative perturbations) $\{-\delta u_j\}$ are applied and the oppositely perturbed metric value is obtained as

$$\delta J_- = J(u_1 - \delta u_1, u_2 - \delta u_2, \ldots, u_N - \delta u_N). \tag{4}$$

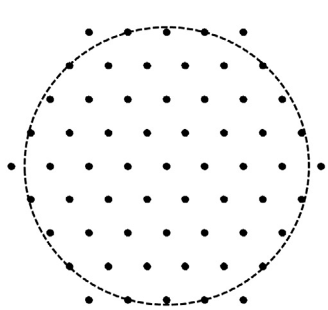

Fig. 2. Actuator distribution of 61-element deformable mirror.

Now the metric variation δJ is obtain as

$$\delta J = \delta J_+ - \delta J_-. \tag{5}$$

If the perturbation signals $\{\delta u_j\}$ are Bernoulli distributed, we can obtain the stochastic parallel gradient descent algorithm for wavefront control method as

$$u^{(k+1)} = \left\{ u_j^{(k+1)} \right\} = \left\{ u_j^{(k)} + \gamma \delta J \delta u_j \right\}, \tag{6}$$

where γ is a learning-rate parameter (positive for the case of metric maximization, negative for minimization and positive in this paper).

2.3. Performance metrics

Performance metric, also known as control cost function, is a very important section in sensorless adaptive optics system. A performance metric must be carefully defined for the particular application, easy to calculate and directly measured by a photodetector or CCD. At present, several metrics have been applied to sensorless adaptive optics system, which mainly include the following:

1) Strehl ratio (SR)

$$\mathrm{SR} = \frac{I(0,0)}{I^{DL}(0,0)}, \tag{7}$$

where $I^{DL}(0, 0)$ is the diffraction-limited intensity distribution achievable in the absence of optical aberrations. The SR can be directly measured by a photo-detector using a pinhole mask. However, it does not seem to be very informative because it does not account for the whole intensity distribution.

2) Power-In-the-Bucket (PIB)

$$\mathrm{PIB} = \frac{\int_0^b I(r) r\, dr}{\int_0^\infty I(r) r\, dr}, \tag{8}$$

where b is the radius of bucket. The PIB can also be directly measured by a photo-detector with a circular-aperture mask.

3) Image sharpness (IS)

$$\mathrm{IS} = \iint I^2(x, y)\, dxdy, \tag{9}$$

where $I(x, y)$ is the intensity distribution. The IS should be measured by a CCD.

4) Mean radius (MR)

$$\mathrm{MR} = \frac{\iint \left| (x, y) - (x_0, y_0) \right| I(x, y)\, dxdy}{\iint I(x, y)\, dxdy}$$
$$x_0 = \frac{\iint x I(x, y)\, dxdy}{\iint I(x, y)\, dxdy}, \tag{10}$$
$$y_0 = \frac{\iint y I(x, y)\, dxdy}{\iint I(x, y)\, dxdy},$$

where (x_0, y_0) is the centroid of the intensity distribution. The MR should be measured by a CCD.

In this paper, a new performance metric is presented, which can be defined as Mask Metric (MM) and described by the following expression

$$\mathrm{MM} = \iint_{\Sigma} \left[1 - \frac{x^2 + y^2}{R^2} \right] I(x, y)\, dxdy, \tag{11}$$

where the mask becomes $1 - (x^2 + y^2)/R^2$ for $(x^2 + y^2) \le R^2$ and zero for otherwise. R is a suitably chosen detector radius and weighted