Optics Communications 310 (2014) 138–149

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Stochastic parallel gradient descent optimization based on decoupling of the software and hardware

Qiang Fu [a,b,c,d,*], Jörg-Uwe Pott [a], Feng Shen [b,c], Changhui Rao [b,c]

[a] Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany
[b] The Laboratory on Adaptive Optics, Institute of Optics and Electronics, Chinese Academy of Science, Chengdu 610209, China
[c] The Key Laboratory on Adaptive Optics, Chinese Academy of Sciences, Chengdu 610209, China
[d] Graduate School of Chinese Academy of Science, Beijing 100039, China

ARTICLE INFO

Article history:
Received 22 February 2013
Received in revised form
3 July 2013
Accepted 18 July 2013
Available online 8 August 2013

Keywords:
Model free
Model-free control
SPGD
Shack–Hartmann sensor
Decoupling methods

ABSTRACT

We classified the decoupled stochastic parallel gradient descent (SPGD) optimization model into two different types: software and hardware decoupling methods. A kind of software decoupling method is then proposed and a kind of hardware decoupling method is also proposed depending on the Shack–Hartmann (S–H) sensor. Using the normal sensor to accelerate the convergence of algorithm, the hardware decoupling method seems a capable realization of decoupled method. Based on the numerical simulation for correction of phase distortion in atmospheric turbulence, our methods are analyzed and compared with basic SPGD model and also other decoupling models, on the aspects of different spatial resolutions, mismatched control channels and noise. The results show that the phase distortion can be compensated after tens iterations with a strong capacity of noise tolerance in our model.

1. Introduction

Many optical systems usually work in the stable environment to keep the high performance. When the stability is disrupted, they usually suffer the performance degradation due to the dynamic perturbation of external environment like the atmospheric turbulence. Thus, the perturbation needs to be removed to improve the performance with regard to the laser beam combination [7], optical imaging in telescope, etc. The active correction methods are usually used to correct the dynamic distortion. The dominating method is the wave-front conjugation correction thanks to the accurate measurement by the wave front sensor (WFS) and the key component deformable mirror (DM) in most cases as corrector. As higher spatial resolution of the imaging system is required, the actuators of DM need to be increased enormously. Estimation shows that the efficiency is lowered as N^2 when the control actuators number N increased and the matrix computation involved in Wave-front Conjugation correction (WFC) is only efficient for low resolution ($N<200$–300)[4]. The direct substitution with high resolution device in the primary system is almost infeasible, while the advanced controlling method is necessary.

The other type of the active correction method is the model-free optimization, which is also named image sharpening correction method and is nearly discarded in the last century due to its low computation performance and heavy computation burden [9]. Nevertheless, with improvement of the computation capability of modern computers and the demand of the high resolution control, it is possible to reactivate this technology which has the advantage of simple structure without wave-front sensors. Several decades ago, the typical optimization algorithm was the climbing mountain algorithm [6] and currently turns to the stochastic parallel gradient descent (SPGD) optimization algorithm [7,8,11,12,14,16]. They have low convergence velocity since the normal performance metric referred to the light intensity is coupled into global control information such as metrics correlated to light intensity [13]. The convergence velocity of SPGD algorithm is reduced by $\sqrt{N}$ when the control channel $\boldsymbol{N}$ increased [10].

A number of researchers have applied the SPGD algorithm successfully to many aspects like coherent beams combination [7], laser beam clean-up [25], atmospheric laser communications [26], etc., where the aberration usually changes slowly. However, very few people concentrate on the improvement of the algorithm performance to extend it to the more general condition. Vorontsov proposed a decoupled SPGD (DSPGD) [13,15] algorithm incorporating wave-front senor aiming to decouple the performance metric to accelerate the convergence. However, the wave-front sensors based on interferometer is not easy to be realized and will make the system more complex. This may turn the merit of

* Corresponding author at: Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany. Tel.: +49 15145685961.
E-mail address: fu@mpia.de (Q. Fu).

0030-4018/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.optcom.2013.07.045

unnecessary WFS to the shortcoming. If and only if the radically enhanced performance can be gained, it is possible to introduce the WFS in SPGD model. In this paper, a simple decoupled method is reconsidered based on atmosphere turbulence without sensors, and also another decoupled method with novel S–H wave-front sensor as a slope sensor is proposed. These are the main concern of the improvement of SPGD algorithm in this paper. This may also be extended to other optimized evolving algorithms, such as genetic algorithm [28], simulated annealing algorithm [29], etc.

In Section 2, we firstly classified the decoupled method into two different types, software and hardware decoupling. In software decoupling, the normal SPGD algorithm depending on the control of Zernike basis instead of voltages of corrector is considered as a decoupling way which is analyzed in a new point of view. In hardware decoupling, we then develop a new model which is delineated explicitly based on normal S–H sensor. In addition, all of the DSPGD control methods are analyzed based on low orders of Zernike aberration in this part. In Section 3, the mismatched model between wave-front sensor and corrector related to the different control channels is analyzed in detail. In Section 4, the noise tolerance is discussed. In Section 5, on the base of numerical simulation, the DSPGD method is investigated through correcting atmospheric turbulence aberration on different spatial resolution(8×8, 16×16 and 32×32 control channels).

2. Development of decoupled SPGD optimization technique

2.1. Overview of both SPGD algorithm and original decoupled methods

Firstly, SPGD algorithm will be reviewed below. It is a model-free iteration control method, which is initialized in 1997 by Vorontsov [11]. The basic iteration equation is

$$u^{n+1}(r)=u^{n}(r)-\gamma\delta J\delta u(r) \tag{1}$$

u is the control vector of voltage which is applied on Deformable Mirror(DM). ***r*** is the spatial coordinate. ***n*** is the iteration number. $\gamma$is the ration scale. J is the optimized target function and is also used to be the performance metric. $\delta J$is the performance metric variation. $\delta u(r)$is the perturbation voltage vector, which follows the Poisson random distribution or Gaussian random distribution on each iterative step, e.g. the probability density distribution$P(\delta u=\pm\tau)=0.5$. $\gamma\delta J\ \delta u(r)$is approximate to gradient $(-du/dt)$ of control vector. There are many performance metrics which are commonly used for the specific applications.

$$J_1=\frac{\iint\sqrt{(x-x')^2+(y-y')^2}I(x,y)\ dx\ dy}{\iint I(x,y)\ dx\ dy} \tag{2}$$

$$J_2=\iint I^2(x,y)\ dx\ dy \tag{3}$$

$$J_3=\iint_R I(x,y)\ dx\ dy \tag{4}$$

$$J_4=\frac{I_{\max f}(x,y)}{I_{thmax f}(x,y)} \tag{5}$$

x·andy·are the light intensity distribution centroid, x and y are the distribution coordinates of light intensity. ***I(x,y)*** is the light intensity on every pixel. $\boldsymbol{I_{maxf}}$ is the experimental maximum light intensity of far field and $\boldsymbol{I_{thmaxf}}$ is the theoretical maximum light intensity of far field. As far as we know, the mean square radius of metric $\boldsymbol{J_1}$ is the most effective performance metric [27] since it combines the light intensity and location information. $\boldsymbol{J_2}$,$\boldsymbol{J_3}$ and $\boldsymbol{J_4}$ are only referred to the entire light intensity or partial intensity. $\boldsymbol{J_4}$ is also the definition of Strehl ration. $I_{max}=\max\left(\iint F\{A\exp(-i\varphi)\}\right)^2$, where ***F{}*** is the symbol of Fourier transform operator; *max*() is the operator of gaining maximum value; ***A*** is the wave-front amplitude and φ is the distortion phase distribution. For different applications, the choice of the performance metrics may be diverse, but all these performance metrics mentioned in this paper are all on the base of Strehl for convenience.

Although the convergence can be accelerated by selecting suitable performance metric, it still needs over hundreds of iterations [27]. The main cause of the slow velocity is the coupled performance metric. It is also analyzed by M.A.Vorontsov [13] who has put forward several general decoupled methods. Here, the concept is repeated and some different ideas are generated. Let us decouple the J in Eq. (1): $J=j_1,j_2\dots,j_n$; j_n is corresponding to the DM actuator distribution. Then the iterative equation is

$$u^{n+1}(r)=u^{n}(r)-\gamma(\delta j_1,\delta j_2,\dots,\delta j_n)\ \delta u(r) \tag{6}$$

The metric variation δj in Eq. (6) is defined in Eq. (4) and usually converges to minimum.

The advantage is that it can accelerate the convergence effectively whereas it makes the system more complex, since it needs new module such as interferometer. There is not a standard module like interferometer realized in the system up to now. So the goal that we want to achieve is to develop a most probable method based on the existing system to explore the decoupling algorithm.

2.2. Software decoupled method

If we only consider the decoupled metric in Eq. 6, the focus is thus to decompose the wave-front on an intelligent way. Because the wave-front can usually be decomposed by orthogonal Zernike basis or Karhunen–Loeve modes [1], the general idea is to look for the correlation between the orthogonal modes and the control vector.

When we consider the aberration correction of the atmospheric turbulence, there is an accelerated SPGD method called Model SPGD correction [12]. This method transforms the optimized voltage vector of corrector to the mode coefficients of wave-front Zernike basis without introducing any extra hardware. It could be defined as a soft decoupled correction method(SDC) while the method proposed in [13] could be defined as a decoupled correction method(HDC) with hardware. In SDC, ***J*** is the decoupled metric on the base of Zernike basis. The interested

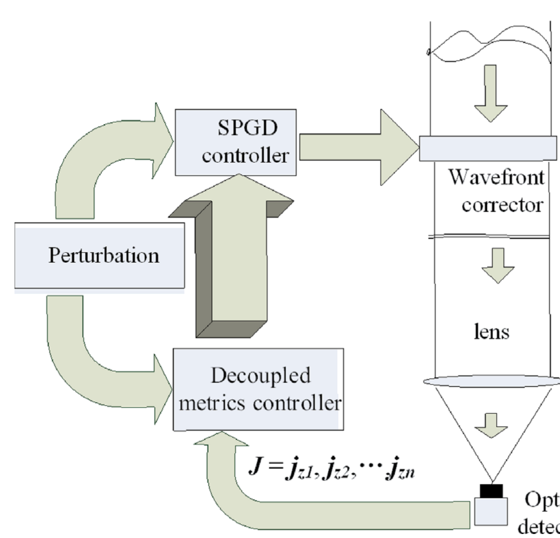

Fig. 1. Soft decoupled SPGD model.