Research in Astron. Astrophys. **2011** Vol. **11** No. **8**, 997–1002
http://www.raa-journal.org *http://www.iop.org/journals/raa*

Research in Astronomy and Astrophysics

Stochastic parallel gradient descent based adaptive optics used for a high contrast imaging coronagraph *

Bing Dong[1], De-Qing Ren[1,2] and Xi Zhang[2]

[1] Physics & Astronomy Department, California State University Northridge, CA, 91330-8268, USA; *bdong@csun.edu*

[2] National Astronomical Observatories / Nanjing Institute of Astronomical Optics & Technology, Chinese Academy of Sciences, Nanjing, 210042, China

Received 2011 January 26; accepted 2011 March 8

Abstract An adaptive optics (AO) system based on a stochastic parallel gradient descent (SPGD) algorithm is proposed to reduce the speckle noises in the optical system of a stellar coronagraph in order to further improve the contrast. The principle of the SPGD algorithm is described briefly and a metric suitable for point source imaging optimization is given. The feasibility and good performance of the SPGD algorithm is demonstrated by an experimental system featured with a 140-actuator deformable mirror and a Hartmann-Shark wavefront sensor. Then the SPGD based AO is applied to a liquid crystal array (LCA) based coronagraph to improve the contrast. The LCA can modulate the incoming light to generate a pupil apodization mask of any pattern. A circular stepped pattern is used in our preliminary experiment and the image contrast shows improvement from 10^{-3} to $10^{-4.5}$ at an angular distance of $2\lambda/D$ after being corrected by SPGD based AO.

Key words: instrumentation: adaptive optics — methods: laboratory — techniques: image processing, coronagraph

1 INTRODUCTION

Direct imaging and characterization of exoplanets have attracted much more attention in recent years, which may help to answer one of the most fundamental scientific questions: “Are we alone in the universe?” To directly image an Earth-like planet orbiting a nearby star in the visible, we have to employ an extremely high-contrast stellar coronagraph at a level of 10^{-10} at small angular separations with a space telescope (a contrast of 10^{-6} to 10^{-7} is needed in the infrared). Many approaches have been proposed to theoretically achieve the 10^{-10} contrast within an inner working angle of $5\lambda/D$ (Guyon et al. 2006b). However, to obtain this high contrast is still very challenging since there are many factors impacting upon its real performance. The most essential limitation of the coronagraph is the speckle noises near the star arising from imperfections in the optical system, which may completely overwhelm any faint planet images. So extremely high quality in the wavefront is required in a high contrast coronagraph.

* Supported by the National Natural Science Foundation of China.

Adaptive optics (AO) has been considered as an effective way to eliminate the impact of background speckles in a coronagraph (Malbet et al. 1995; Give'On et al. 2007). In recent years, the AO system employing a high actuator-density deformable mirror (DM) and focal-plane wavefront sensing-like phase-retrieval has been successfully demonstrated both in laboratory and on ground-based telescopes to eliminate speckle noises in a coronagraph (Trauger & Traub 2007; Serabyn et al. 2010). Focal-plane wavefront sensing is immune to non-common path errors and chromaticity and also simplifies the optical system, so it is optimal for high contrast imaging (Guyon et al. 2006a). However, the existing approaches are highly dependent on high accuracy estimation of the pupil wavefront (about $\lambda/2000$ root-mean-squared (RMS)) and high accuracy positioning of the DM actuators (less than 0.2 nm). Related wavefront sensing algorithms are somewhat complicated. In this paper, we consider using a focal-plane wavefront sensing method named stochastic parallel gradient descent (SPGD) to reduce the speckle noises in a coronagraph. Without an estimation of the wavefront, the DM is driven directly by measurements in the image plane of SPGD. SPGD is also a model-free method so it is very robust to model errors of DM. After first being developed by Vorontsov (Vorontsov et al. 1997), the SPGD method has been successfully used in many scenarios (Weyrauch & Vorontsov 2005; Zhou et al. 2009). As far as we know, it has not been used in a high contrast imaging coronagraph.

We are particularly interested in one kind of pupil-apodized coronagraph which uses a step-transmission filter (Ren & Zhu 2007; Ren et al. 2010). Recently, Ren & Zhu first proposed a high-contrast imaging coronagraph that integrates a liquid crystal array (LCA) and a DM for active pupil apodization and phase correction respectively (Ren & Zhu 2011). Avoiding the difficulty of fabricating a precise filter mask, this new approach is low-cost and flexible to work with in any type of telescope. Nevertheless, the wavefront errors in the optical system, especially the phase error of the LCA, is still our concern and must be suppressed by AO. In our case, AO is mainly used to correct quasi-static errors of the optical system so a high closed-loop bandwidth is not necessary. In Section 2, we briefly present the principle of the SPGD algorithm and give a metric suitable for point source imaging optimization. Then an experimental system is introduced to demonstrate the feasibility and effectiveness of the SPGD algorithm in Section 3. The SPGD based AO is applied to an LCA based coronagraph to improve the image contrast and the result is given. Finally, we present our conclusions.

2 PRINCIPLE OF SPGD ALGORITHM

The SPGD algorithm is an improved version of the well-known steepest descent algorithm. It applies small random perturbations to all control parameters (voltages of actuators) simultaneously and then evaluates the gradient variation of the system's performance metric. The wavefront errors can be compensated by optimizing the metric that is calculated from measurable data, like intensity distributions, in the focal plane. The control signals are updated during the iteration process of the SPGD algorithm according to the following rule

$$\boldsymbol{u}^{k+1} = \boldsymbol{u}^k - \gamma \delta J^k \delta \boldsymbol{u}^k, \tag{1}$$

where k is the iteration number; $\boldsymbol{u} = \{u_1, u_2, \ldots, u_N\}$ is the control signal vector, N is the control channel number (i.e. the number of actuators); γ is the gain coefficient which is positive for minimizing the metric and negative for maximizing the metric; $\delta \boldsymbol{u}$ denotes small random perturbations that have identical amplitudes and Bernoulli probability distribution; δJ is the variation of the system's performance metric.

$$\delta J = J(\boldsymbol{u} + \delta \boldsymbol{u}) - J(\boldsymbol{u}) = J(u_1 + \delta u_1, ..., u_j + \delta u_j, ...u_N + \delta u_N) - J(u_1, ..., u_j, ...u_N). \tag{2}$$

To improve the estimation accuracy of δJ, a two-sided perturbation is used as

$$\delta J = J_+ - J_- = J(\boldsymbol{u} + \delta \boldsymbol{u}/2) - J(\boldsymbol{u} - \delta \boldsymbol{u}/2). \tag{3}$$

The gain coefficient γ, which adapts to the metric J, is used to accelerate the convergence.

$$\gamma^{k+1} = \gamma^k \cdot J^k \quad \text{(to minimize } J\text{)}, \tag{4}$$

or

$$\gamma^{k+1} = \frac{\gamma^k}{J^k} \quad \text{(to maximize } J\text{)}. \tag{5}$$

In our case, a point source will be imaged on the focal plane and several metrics can be used to evaluate the system's performance (Chen et al. 2009). Here the mean radius of the image spot is chosen as the performance metric to be minimized

$$J = \frac{\iint \sqrt{\left(x - x'\right)^2 + \left(y - y'\right)^2} I\left(x, y\right) dxdy}{\iint I\left(x, y\right) dxdy}, \tag{6}$$

where $I\left(x, y\right)$ is the intensity distribution in the focal plane; $\left(x', y'\right)$ is the image centroid.

3 EXPERIMENTAL DEMONSTRATIONS

The experimental system for demonstrating the SPGD algorithm is shown in Figure 1. The laser light (λ=632.8 nm) is focused by a microscope objective and then passes through a pinhole to simulate a point source. The collimated beam then passes through a transparent phase plate which induces static wavefront errors. Then the beam hits a DM which has 140 active actuators within a clear aperture of 4.4 mm. This DM is based on Micro-Electro-Mechanical System (MEMS) technology and has a good initial surface quality (RMS error $<$ 20 nm). After hitting the DM, the wavefront is split into two parts by a beam splitter. One part is imaged on the camera and the image data are acquired by the SPGD controller to command the DM. The other part goes to a Hartmann-Shark wavefront sensor (H-S WFS) that measures the wavefront error before and after correction for comparison.

The distorted wavefront caused by the phase plate and related far-field images before the DM correction are depicted in Figure 2, where the initial RMS wavefront error is 0.21λ. The wavefront and far-field image after correction are shown in Figure 3, where the RMS wavefront error is reduced to 0.041λ. The wavefront error is greatly reduced after the correction and the far-field image is concentrated in a small circle. The evolution curve of the metric during the correction process is depicted in Figure 4.

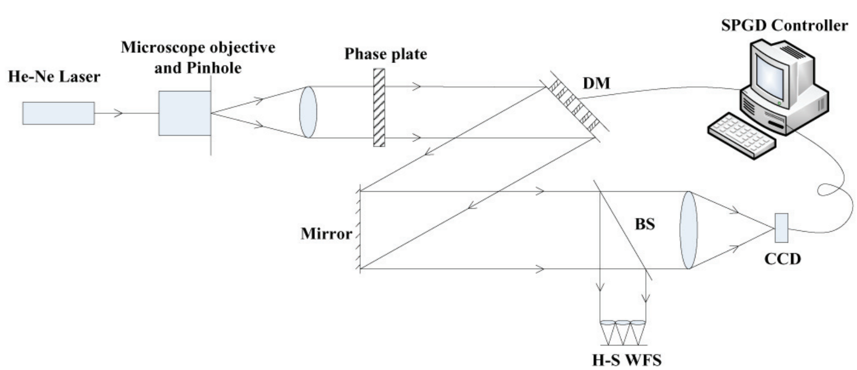

Fig. 1 Experimental system for SPGD algorithm demonstration.

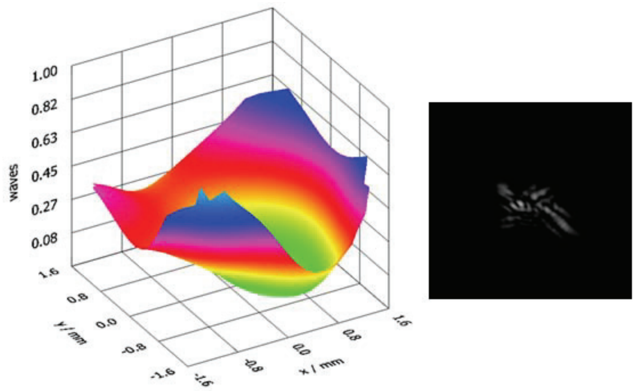

Fig. 2 Distorted wavefront (*left*, PV=0.91λ; RMS=0.21λ) and far-field image (*right*).

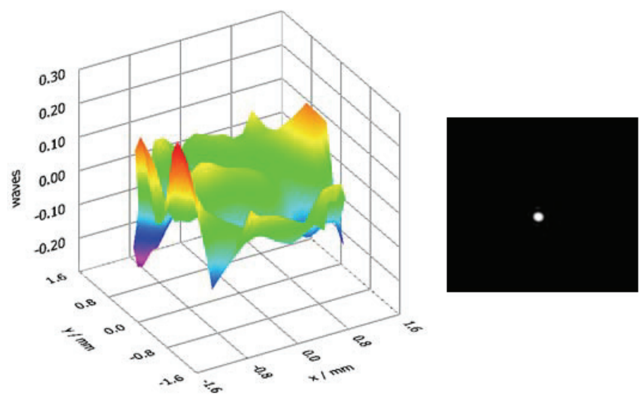

Fig. 3 Corrected wavefront (*left*, PV=0.34λ; RMS=0.041λ) and far-field image (*right*).

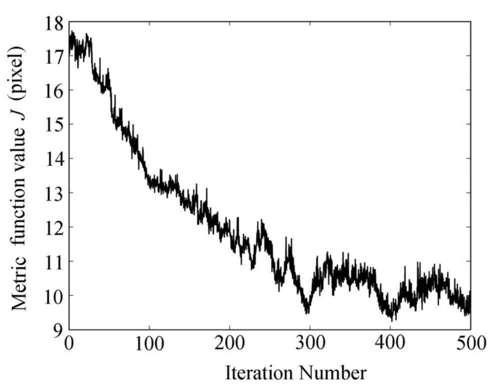

Fig. 4 Evolution curve of the metric J.

The metric achieves convergence in about 250 iterations taking half a minute. The elapsed time of the correction is dependent on the hardware configuration including the actuator number, the image acquisition speed and the software efficiency.

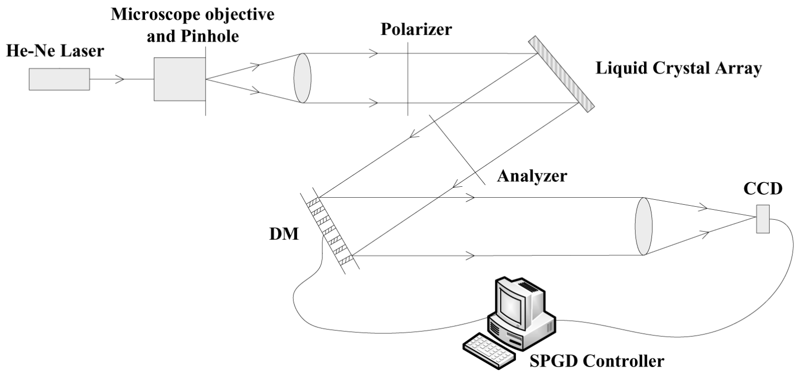

Fig. 5 Layout of SPGD AO used in the LCA based coronagraph.

Fig. 6 Apodized far-field image before (*left*) and after (*right*) correction.

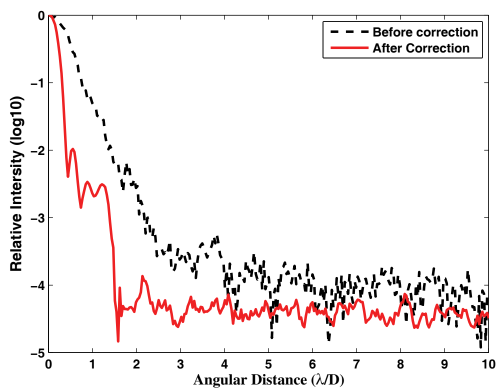

Fig. 7 Contrast profile of coronagraph before and after AO correction.

It is easy to apply the SPGD method to the coronagraph based on the liquid crystal array. The experimental lay-out is shown in Figure 5. The reflective liquid crystal array, sandwiched by a polarizer and an analyzer, serves as a spatial light modulator to modulate the amplitude of incoming light to a pre-designed pattern. Here a circular stepped pattern is generated by the liquid crystal array to form an apodized pupil (Ren & Zhu 2011; Dou et al. 2010). In this configuration, however, the H-S WFS cannot be used to obtain the phase map because of the pupil apodization.

The apodized far-field images of the coronagraph before and after the DM correction are shown in Figure 6. The image contrast is improved from 10^{-3} to $10^{-4.5}$ at an angular distance larger than 2λ/D after correction, however, the process is still not achieving its theoretical value of $10^{-5.5}$ (see Fig. 7).

In high contrast imaging coronagraph applications, we have to control the intensities over a wide dynamic range. The output of the camera currently in operation has only an 8-bit dynamic range that is not enough to sample the low intensity areas some distance away from the PSF center, which leaves the intensities out of the main lobe undetected and thus uncontrolled by the SPGD optimization. Although we can extend the exposure time to acquire more image information, this will lead to image saturation and unsteadiness in the correction process. A possible solution is to use a camera with a wider dynamic range such as 16-bit or more. Also, we can normalize several CCD images with different exposure times to one high-dynamic-range image which will be used to evaluate the system metric in the SPGD algorithm while, however, sacrificing speed. Another factor that affects the performance of the SPGD AO in speckle suppression of the coronagraph is the number of actuators in the DM which determines the corrective ability in the spatial frequency domain. In classical speckle nulling or the "dark hole" algorithm, the number of actuators in the DM is usually larger than 1000 or more, which is an order of magnitude higher than ours. High actuator-density DM should be adopted in our system in the future. We have made some efforts to calibrate the liquid crystal array to reduce its nonuniform response between different pixels, but it still has some impact on the image contrast that prevents it from approaching the design value.

4 CONCLUSIONS

SPGD based AO is a promising technique to eliminate the speckle noises and improve the contrast of an imaging coronagraph. We have demonstrated the feasibility and good performance of SPGD based AO in the laboratory and then applied it to the liquid crystal array based coronagraph. The image contrast is enhanced from 10^{-3} to $10^{-4.5}$ after correction. Due to the limitation of dynamic range of the detector, the number of actuators in the DM and the nonuniform response of the liquid crystal array, the image contrast still has not come close to achieving its design value and related problems should be discussed further in future publications.

Acknowledgements This work was supported by the National Science Foundation under Grant ATM-0841440, the National Natural Science Foundation of China (Grant Nos. 10873024 and 11003031), as well as the National Astronomical Observatories' Special Fund for Astronomy-2009.

References

Chen, B., Yang, H. Z., Zhang, J. B., Li, X. Y., & Jiang, W. H. 2009, Acta Optica Sin. (in Chinese), 29, 1143
Dou, J., Ren, D., & Zhu, Y. 2010, Research in Astronomy and Astrophysics, 10, 189
Give'On, A., Belikov, R., Shaklan, S., & Kasdin, J. 2007, Optics Express, 15, 12338
Guyon, O., Gallet, B., Pluzhnik, E. A., Takami, H., & Tamura, M. 2006a, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 6272
Guyon, O., Pluzhnik, E. A., Kuchner, M. J., Collins, B., & Ridgway, S. T. 2006b, ApJS, 167, 81
Malbet, F., Yu, J. W., & Shao, M. 1995, PASP, 107, 386
Ren, D., Dou, J., & Zhu, Y. 2010, PASP, 122, 590
Ren, D., & Zhu, Y. 2007, PASP, 119, 1063
Ren, D., & Zhu, Y. 2011, PASP, 123, 341
Serabyn, E., Mawet, D., & Burruss, R. 2010, Nature, 464, 1018
Trauger, J. T., & Traub, W. A. 2007, Nature, 446, 771
Vorontsov, M. A., Carhart, G. W., & Ricklin, J. C. 1997, Optics Letters, 22, 907
Weyrauch, T., & Vorontsov, M. A. 2005, Appl. Opt., 44, 6388
Zhou, P., Ma, Y., Wang, X., et al. 2009, Optics Letters, 34, 2939