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Numerical and experimental study on liquid crystal optical phased array beam steering combined with stochastic parallel gradient descent algorithm

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ABSTRACT

In this paper, we present numerical and experimental study on beam steering with liquid-crystal optical phased array (LC-OPA) by means of stochastic parallel gradient descent (SPGD) algorithm. The numerical simulation, which is mainly based on the evolution of power-in-bucket (PIB), indicates that the beam steering strategy with LC-OPA is relatively robust, and the algorithm performs well most of the time. The results also reveal that the performance of SPGD algorithm is influenced by the order of Zernike polynomials, the radius of bucket and the steering angle. The order of Zernike polynomials and the radius of bucket are optimized to improve the accuracy and convergence of the algorithm. In a proof-of-concept experiment, the feasibility of the beam steering strategy with LC-OPA is demonstrated.

1. Introduction

Beam steering techniques have been played an important role in laser radar, free space laser communication, tracking and aiming area [1–4]. Traditional beam steering always relies on bulk mechanic systems. Novel nonmechanical beam steering methods make it possible for the optical system to be simple and integrated. As one of the novel nonmechanical beam steering methods, optical phased array (OPA) technique can steer beam with agile beam control. Liquid crystal optical phased array (LC-OPA) has been highly developed in recent years since professor McManamon raised the idea of LC-OPA again in 2007 [1]. It has been widely applied in many fields such as beam tracking, beam shaping and optical tweezers [5–8], for its high spatial resolution and programmable controller.

Up to now, in order to provide high steering efficiency, large steering angle, much work has been done [9–11]. Some defects still exist in the beam steering method. Steering errors such as beam jittering and wavefront distortion cannot be avoided during the beam transmission by the conventional beam steering method; the modulated phase still needs to be calculated in advance; the conventional method cannot steer beam to the target real-time.

In this paper, the concept of SPGD beam steering with LC-OPA is introduced, which can steer the beam dynamically with closed loop control. The numerical study on the SPGD beam steering strategy with LC-OPA is represented in detail and a proof-of-concept experiment is shown. The feasibility of the method is proven and some of the parameters in the method are chosen properly to optimize the algorithm, and conclusions of convergence of the SPGD algorithm are drawn in the end.

2. Control algorithm

Stochastic parallel gradient descent (SPGD) algorithm has been reported and used widely in adaptive optical (AO) system [12–15]. In this paper, the SPGD algorithm is described by the Zernike polynomials. With the modes completely defined, wavefront $W(r,\theta)$ can be written as a Zernike series with coefficients a_i given:

$$W(r,\theta)=\sum_{i=1}^{\infty}a_iZ_i(r,\theta), \tag{1}$$

where $Z_i(r,\theta)$ is the ith Zernike polynomial with polar normalized pupil coordinate (r, θ) [16] Actually in beam steering, especially in beam deflection, phase tilt is the most important factor. With the 1th and 2th Zernike polynomials, phase tilt $W_t(r, \theta)$ can be expressed [17]:

$$W_t(r,\theta)=a\cdot Z_1(r,\theta)+b\cdot Z_2(r,\theta), \tag{2}$$

where a and b are phase coefficients. With SPGD algorithm, the coefficients can be acquired. The parameter N_z, which means the

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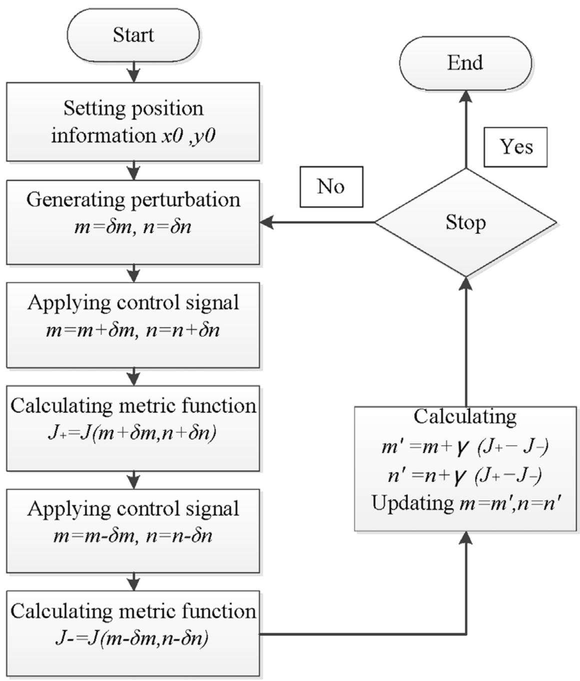

Fig. 1. Schematic representation of the SPGD algorithm for controlling LC-OPA beam steering system.

Table 1
Simulation parameters.

Physical quantity	Magnitude
Working wavelength	1.064 μm
Pixel size of CCD	0.05 mm
Sample rate number	512
Waist of Gaussian beam	2 mm
Focus of lens	0.1 m

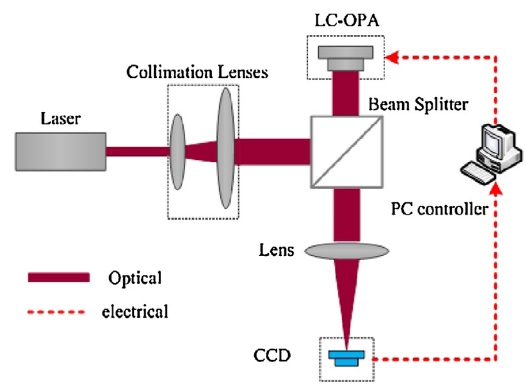

Fig. 2. Setup of LC-OPA beam steering system.

order of Zernike polynomials, is defined. For example, when N_z equals 5, it means that the wavefront is expressed by the first five different Zernike polynomials. δ and γ are parameters of the control program in SPGD algorithm [12]. The only metric function can be used in beam steering is power-in-the-bucket (PIB) for which includes position information. And the PIB can be expressed as:

$$\mathrm{PIB} = \frac{I_{r-fact}}{I_{r-\mathrm{ideal}(x0,y0)}} \quad (3)$$

where $I_{r\text{-}ideal}$ means the power in bucket without phase modulation in the position (0, 0), and $I_{r\text{-}ideal(x0,\,y0)}$ means the power in bucket with phase modulation in the position (x0, y0), and the position (x0, y0) is the ideal position we expect to steer. At first the radius of the bucket equals the waist of Gaussian, which is w_0.

The schematic representation of SPGD algorithm is shown in Fig. 1 and detailed steps of SPGD algorithm for controlling the LC-OPA beam steering system are as follows [14].

(i) Set original parameters (x0, y0). These two parameters contain information of steering angle expected to realize in this beam steering system.
(ii) Generate a group of stochastic phase perturbations δm and δn.
(iii) Apply the phase perturbation ($m-\delta m$, $n-\delta n$) and ($m+\delta m$, $n+\delta n$) to the LC-OPA, the LC-OPA realizes phase modulation on the beam, then the corresponding metric functions $J-$ and $J+$ can be calculated from the information on CCD camera.
(iv) Update phase distribution m and n.
(v) Judge the metric function and decide whether continue the procedure. When J reaches a maximum value, it means the algorithm terminated.

3. Numerical simulation results and discussion

In this section, we perform feasibility validation on LC-OPA beam steering strategy using the SPGD algorithm. The basic simulation principle and the program procedure are clarified in the frontal section. According to Fraunhofer diffraction, the field distribution can be calculated. The main simulation parameters are shown in Table 1, and the simulation system is shown in Fig. 2.

As shown in Fig. 2, a laser beam is expanded by collimation lenses. Reflected by the beam splitter (BS), part of the beam enters into the LC-OPA. With phase modulation of the LC-OPA, the beam is deflected and then is focused on the CCD which is interfaced with computer. With acquiring intensity distribution of the beam on the CCD and loop control of the LC-OPA, the beam steering strategy can be realized. Both of numerical simulation and experiment are done with this system. Suppose that the LC-OPA can provide high accuracy phase modulation and there are neither environmental factors nor devices factors will influence the experiment.

Numerical simulation results of beam steering with phase tilts only are shown in Fig. 3.

The intensity distribution of steered beam and unsteered beam are given in Fig. 3(a) and (b) respectively. The steering angle of the beam is 6.6 mrad in Fig. 3(b). In Fig. 3(c), the evolution of PIB is depicted. When PIB becomes stable, the beam has been steered to the ideal position we expected to. However, the evolution of PIB is different each time. Perhaps the stochastic phase perturbations are the reason for the difference, but the final value of PIB is almost the same to a fixed steering angle. We carry out further calculation to study the factors of this phenomenon and to optimize the beam steering method.

3.1. *Effect of* N_z

As the order of Zernike polynomials, $\sqrt{N_z}$ is in linear relation with the convergence of SPGD algorithm [17]. The phase aberrations can also be compensated by high orders of Zernike polynomials the phase. Due to the existing of phase aberrations, there exist other diffractions. By increasing of N_z, primary phase aberrations can be compensated and these diffractions can be obliterated. Since both of primary astigmatism, primary coma and trefoil are expressed with two independent Zernike polynomials, effects of N_z for the SPGD beam steering are investigated by means of even values N_z.

From the results above, it shows that the SPGD algorithm is effective when N_z equals 2, 4 and 6. Once random value and average