Modal vs. Zonal Wavefront-sensorless Adaptive Optics for Free-space Laser Communications

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Abstract: Atmospheric effects limit the performance of any electro-optical system. Tasks such as laser communication and delivery of directed energy are significantly affected by turbulence and refraction. A correction of atmospheric effects on the propagation of light can be done by adaptive optics (AO). Unconventional wavefront sensing strategies are being developed to provide alternatives for measuring the wavefront deformation of a laser beam propagating through strong turbulence and/or along a horizontal-path. In this paper we present results from two "wavefront-sensorless" approaches: stochastic parallel gradient descent (SPGD) and its modal version (M-SPGD).

OCIS codes: (010.1330) Atmospheric turbulence, (010.1080) Active or adaptive optics

1. Introduction

The most widely applied wavefront sensor for the measurement of turbulence-induced phase errors is the Shack-Hartmann sensor. This sensor has several advantages, the most significant being its clear principle of operation. On the other hand, wavefront- sensing requires the redirection of optical power to the sensor, diminishing the available power at the receiver in free-space optical communication systems. Furthermore, the robustness of traditional wavefront reconstruction algorithms using wavefront- sensing becomes more vulnerable under strong scintillation conditions [1].

In scenarios where wavefront measurement is either impossible, because of e.g. very high turbulence, or not necessary, e.g. in medicine where optical aberrations introduced by human body into the imaging equipment are static or slowly-evolving, the concept of "wavefront-sensorless" AO has become established [2]. Here, use is made of "smart" algorithms which "guess" various combinations of optical deformations until an improvement in image or laser beam quality is observed. Naturally, when applied to strong atmospheric turbulence the methods must be exceptionally fast in their convergence rate. The most famous method, the stochastic parallel gradient descent (SPGD) [3], is inherently "blind", i.e. it does not make any assumptions about the nature of the aberrations and the propagation formalism through an optical system.

In order to improve the convergence rate of SPGD the modal version of the algorithm, M-SPGD, was proposed [4, 5]. In SPGD, one perturbs randomly the actuators on the deformable mirror and the image or beam quality metric is checked for improvement. This can become a highly-dimensional problem for modern deformable mirrors with many actuators. To reduce the number of degrees of freedom one can project the actuator space onto an orthogonal modal basis, e.g. Zernike polynomials and perturb these instead of actuators. Additional advantage of this approach is that one can include known turbulence statistics into the algorithm e.g. by optimizing gain of the algorithm for each mode (it is well known that low-order modes such as tip, tilt and defocus have more influence on image/beam quality than the higher-order modes).

2. Methods

Traditional SPGD algorithm can be written in the following way. Firstly, at each iteration m random positive and negative perturbations $\pm\gamma_n^m\,\delta u$, where γ_n^m is a random sign vector and δu is the perturbation factor, are applied to the actuators u_n:

$$u_n^{m+} = u_n^m + \gamma_n^m\,\delta u \qquad (1)$$

$$u_n^{m-} = u_n^m - \gamma_n^m\,\delta u \qquad (2)$$

Subsequently, change in the quality metric, in our case the Strehl ratio, is measured:

$$\delta J^m = J(u_n^{m+}) - J(u_n^{m-}) \qquad (3)$$

Then, update of the control signal multiplied by the gain G, follows as:

$$u_n^{m+1} = u_n^m + G\,\delta J^m\,\gamma_n^m\,\delta u \tag{4}$$

The convergence speed and correction gain highly depend on the choice of the parameters G and perturbation factor δu.

In our implementation of M-SPGD the positive and negative perturbations from Eq. 1 are applied to Zernike modes and not to actuators. Therefore, at each iteration, the current vector of Zernike coefficients has to be projected onto actuator voltages in order to drive the deformable mirror. This causes an additional overhead but the convergence rate of M-SPGD is still significantly increased as compared to traditional SPGD.

Initially, we compared both approaches through simulations. Atmospheric phase-screens were created with the Fourier-based method. We have indeed demonstrated faster convergence rate of the M-SPGD algorithm as compared to the traditional SPGD. In Fig. 1 the evolution of the Strehl ratio vs. iteration number is shown for both approaches. Although classic SPGD achieves higher Strehl ratios, it converges slower than M-SPGD. In the interesting regime of less than 100 iterations M-SPGD performs better than SPGD.

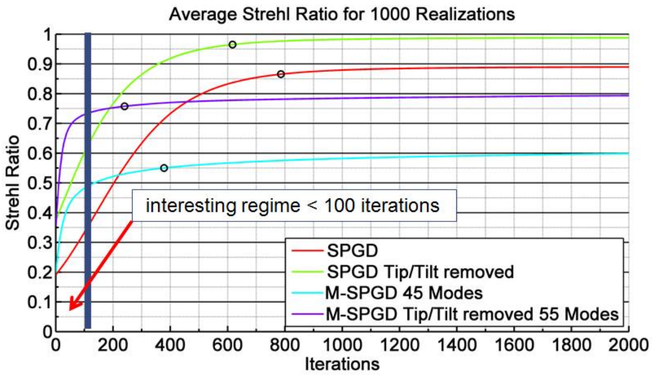

Fig. 1. Illustration of convergence of SPGD and M-SPGD algorithms. Black circles denote points on the curves where the quality metric, here the Strehl ratio, starts to change by less than 10^{-4}. The blue vertical line denotes the region of less than 100 iterations which for practical reasons is the most interesting.

3. Experiments

The setup for testing M-SPGD is shown schematically in the left panel of Fig. 2. A photograph of the bread-board demonstrator is shown in the right panel. The setup uses the communications wavelength of 1.55 μm. As light source we used a fiber laser (NKT Photonics, Koheras Adjustik C15). Aberrations (atmospheric phase-screens) were introduced by way of the spatial light modulator (SLM: Hamamatsu, LCOS-SLM X13138-08). As corrector a deformable mirror (DM) with 12 × 12 actuators was used (BMC, Multi DM -CDM). As a receiver we used a 43 GHz balanced photodetector (Finisar, BPDV21x0R).

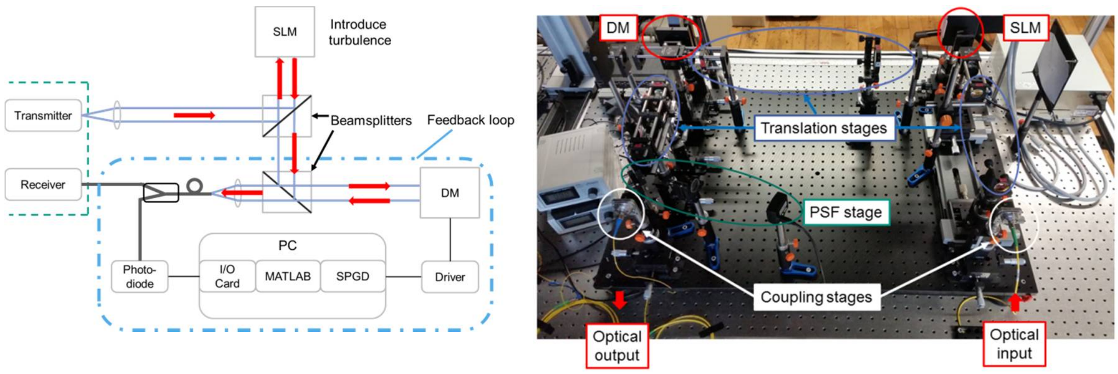

Fig. 2. Left: Diagram showing the setup for testing M-SPGD algorithm for the laser communications applications. Simulated turbulence (a phase screen from the Fourier-based method) is introduced into the setup through the spatial light modulator (SLM). Right: Actual optical system.

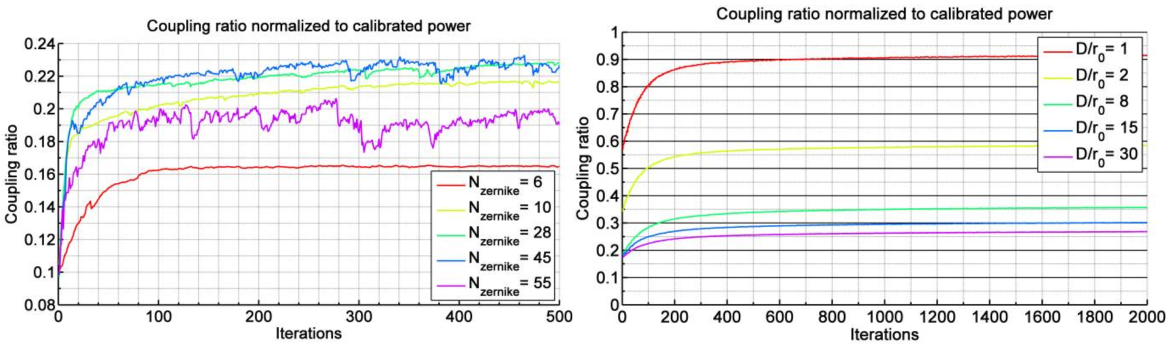

Fig. 3. Left: Diagram showing the influence of different numbers of Zernike modes on M-SPGD's performance. Right: Illustration of convergence of classic SPGD for different turbulence conditions quantified as D/r_0.

After initial runs to establish the optimal parameters G and δu for both versions of SPGD, we estimated the optimal number of Zernike Modes for M-SPGD under a low turbulence level given by the normalized turbulence strength $D/r_0 = 5$, where D is the diameter of the beam at the SLM and r_0 is Fried's coherence length (see Fig. 3, left). The coupling ratio, defined as the output power under turbulence normalized by the output power without turbulence, increases with increasing number of Zernike modes introduced to the DM. After exceeding a certain number of modes, any further increase provides no increase in coupling ratio. To the contrary, a decrease in metric is observed. At this point the algorithm is not capable to optimize the coefficients of the high-order modes because their impact on the phase variance is smaller than for low-order modes, leading to decrease in coupling ratio.

Subsequently we executed the tests for a range of different turbulence scenarios (see Fig. 3, right, for classic SPGD results). Any increase of the turbulence strength leads to a decrease in the coupling ratio, following Noll's theory [6]. The algorithm is not able to achieve 100% coupling ratio even for very weak turbulence due to the resolution mismatch between SLM and DM (AO fitting error). Nevertheless, the system is able to emulate the desired turbulence conditions correctly and achieve fair correction results.

4. Conclusions

It has been shown that it is possible to avoid using a wavefront sensor in an AO system. In the wavefront-sensorless approach we have tested two algorithms: SPGD and its modal version, M-SPGD. We have found faster convergence rate of the latter. More work on this approach is needed. In particular, we will research possible gains in convergence rate of M-SPGD with the inclusion of extra physical knowledge about turbulence. Additionally, we plan to introduce dynamic turbulence in the setup by way of moving and "boiling" phase-screens. Then, it should be possible to analyze whether the faster convergence of M-SPGD offsets its apparent inferiority to classic SPGD in terms of ultimately achievable coupling ratio. Additionally, we plan to connect the bread-board to a wavelength multiplexing system and measure the achievable data rates and bit-error rates over a range of atmospheric conditions. The longtime goal is to establish an 8 km horizontal free space optical coherent communication link that uses wavelength division multiplexing and wavefront-sensorless architectures.

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