Adaptative compensation on free-space optical coherent systems

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Abstract - New, affordable adaptive compensation methods and technologies can help to improve substantially the performance and reliability of coherent optical systems in the atmosphere. The use of adaptive optics to mitigate turbulence-induced phase fluctuations in receivers employing coherent detection is poised to reduce performance penalties enabling a more sensitive generation of coherent instruments and applications.

In this work we describe the implementation of an optical coherent receiver that uses phase compensation and adaptative optic techniques, as well as digital architectures for signal processing and control. We show experimentally the viability of the approach to improve the efficiency and sensitivity of the receiver. Both free-space optical communications and coherent lidar systems may benefit from use of the methods and techniques derived from this research.

1. Introduction

Atmospheric turbulence restricts the received power levels in optical systems and degrades their overall performance [1]. Free space optical systems exhibit severe temporal fading associate with the turbulence-induced optical amplitude fluctuations which increases the error at the receiver and decreases the system capacity..

Adaptive optics (AO) can be used to compensate static or dynamic aberrations of a light beam after propagation through a distorting medium. In general, an adaptative optical system is composed by a wavefront actuator, a sensor to quantify the wave-front error and a feedback control algorithm to link these two elements in real time. These systems have been historically large and expensive for widespread applications [2].

Significant advances in the technology at 1550 nm wavelength, that can be applicable to free-space optical systems, are motivating several improvements in coherent (synchronous) systems due to the fact that the strength of the scillation decreases as the inverse of the wavelength. Also, a shorter wavelength allows a more compact component design and a lower power consumption.

In this paper we present a practical implementation of a compact adaptative optical system at 1550 nm based on a wave-front sensorless architecture. This experimental set-up reduces the complexity and the cost of the adaptative optic system while it provides fast and effective wave-front correction, which could potentially benefit many applications through turbulence optical channels.

Our adaptative system consist on a fast steering mirror to control the tip/tilt deviations, a 36-element deformable mirror (DM) fabricated using MEMS technology manufactured by Boston Micromachines which can operate at a frequency rate of 3Khz and a stochastic parallel gradient descent algorithm (SPGD) focused on the maximization of the coupled optical power by means of an iterative blind optimization algorithm.

2. Adaptative Optics Architecture for Free-Space Optical systems

Historically, conventional AO systems have been successfully implemented using a wave-front sensing and reconstruction. In order to achieve a valid sensing, a portion of the received light beam has to be directed to a wave-front sensor. This fact reduces the system sensitivity and increase the cost of the system because of the need of a wavefront sensor.

This scenario has now changed due mainly to the development of new technologies that allow us to apply estimation techniques, such as SPDG, which are based on iterative methods and blind optimization algorithms of a metric value of the AO system. These novel techniques were basically disregarded due to the high limitations imposed by the software time-consuming operations and the control bandwidth requirements.

Our system is based on an adaptative receiver which improves focusing the received beam on the receiver by using a metric value from the receiver as a feedback signal. This signal is used to drive the closed-loop algorithm, as shown in Figure 1. The closed-loop operation of the architecture imposes a theoretical bandwidth response limitation for this approach. The feedback signal sent from the coherent detector to the SPDG algorithm can be any metric calculated at the receiver. The implemented adaptative system uses the coupled signal power measure at the receiver.

3. Experimental Set-up

The experimental setup for the adaptative optical system is illustrated in Fig. 2. A 2-mm-diameter collimated laser beam at a wavelength of 1550nm arrives to the system. A first mirror acts, in conjugation with the fast steering mirror, as a Z-Mirror that allows us to calibrate the system when no aberration is introduced in order to maximize the coupled power at the fiber coupling stage. The fast steering mirror is intended to correct the low-order distortions of the aberrated waveform (tip and tilt), which corresponds to the *x* and *y* axis respectively. This device has a frequency rate of 1.3 kHz, a closed loop tilt angle of 2 mrad and an angular resolution of 0.02 µrad.

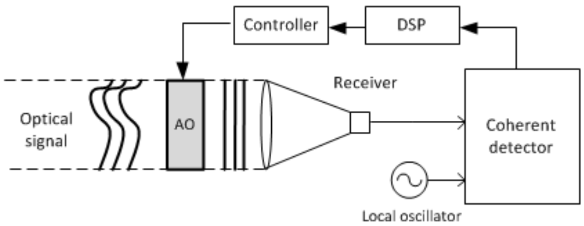


Fig. 1. *Adaptative Optics Architecture for coherent systems. Wavefront distortion on the incoming optical signal is corrected by the adaptative optics (AO) which are controlled by the output of the SPDG algorithm using the metrics obtained in the coherent receiver.*

The reflected beam is directed into a structure that acts as a free space circulator consisting on a half wave-plate, a polarizing beam splitter (PBS), the deformable mirror (DM) and a quarter wave-plate. The benefits of this arquitecture are basically two. First, the room used is minimized and the system becomes very manageable and easy to embed or transport. Second, the whole effective area of the DM is used. This means that every actuator surface and stroke of the DM is being fully used, which increase the compensation efficiency [3], specially mitigating the high-order wave distortions from atmospheric turbulence.

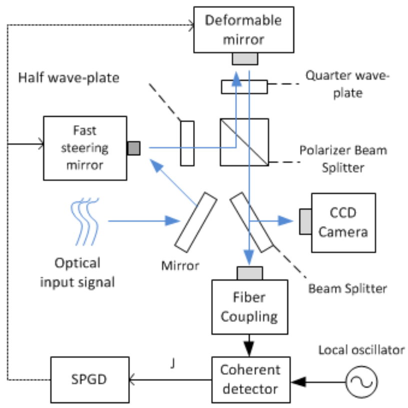


Fig. 2. *A 2-mm-diameter collimated laser beam at a wavelength of 1550nm arrives to the system. A first mirror acts, in conjugation with the fast steering mirror as a Z-Mirror that allows us to calibrate the system when no aberration is introduced. The light is sent through a half wave plate to change its polarization. The output polarization must be that one that maximizes the reflection on the PBS. Then, the whole linearly polarized signal is sent to the quarter wave-plate, which converts it to circular polarization. The light hits the DM, where the handedness of polarized light is reversed and then translated into horizontal polarization. A beam splitter send a sample to a CCD camera and the 92% of the power is sent to the coherent detector through a fiber coupling stage. The SPGD uses the metric value J to generate the control signal to the fast and deformable mirrors.*

The light coming from the fast steering mirror is sent through a half wave plate to change its polarization. The output polarization must be that one that maximizes the reflection on the PBS. Then, the whole linearly polarized signal is sent to the quarter wave-plate, which converts it to circular polarization. The light beam hits the DM and the handedness of polarized light is reversed. Then, it is translated into horizontal polarization by the same quarter wave plate while going in the opposite direction. A 8% reflection beam splitter divides the light beam into two beams, one going to the fiber coupling stage and the other going to a CCD camera at 1550nm, which will act as a monitoring signal.

The coherent detector receives the fiber optical signal and evaluates the metric value *J*, which is sent to the SPGD algorithm. The control signals produced by the SPGD are amplified by and fed into the fast steering mirror and DM. The wavefront correction is then performed in an iterative manner working at 1200 iterations per second.

The theory of the SPGD consists on applying, in parallel, stochastic perturbations on the different mirrors involved and the measurement of the subsequent change in the performance metric. From the change in the performance metric, the SPGD estimates the value of the gradient of the performance metric for each mirror control channel. All the mirror control channels can then be updated in parallel based on the gradient estimates. The resulting effect is that the SPGD climbs the gradient in the performance metric, optimizes the mirror control signals, and maximizes the performance metric.

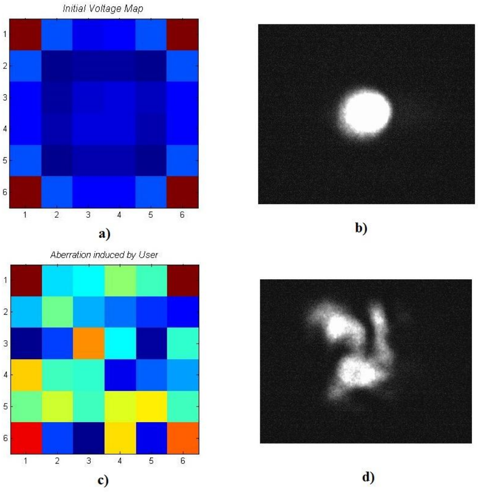


Fig. 3. *Perturbation introduced by the DM and its corresponding beam light image recorded from the CCD camera.* ***a)*** *Phase map is a flat mirror, which implies no aberration in* ***b)****, and* ***c)*** *is a random phase map which produces the image on* ***d)****.*

In order to generate aberrations, a random phase map is sent to the DM and fast steering mirror. These random perturbations diminish the power coupled into the fiber and alter the beam light shape observed with the CCD. In Fig. 3 different beam light image are shown when different random phase maps are introduced in the DM.

4. Results

The adaptative optical system designed and implemented is demonstrated by the measure of the normalized optical power coupled into a single-mode fiber. The maximum coupling efficiency achieved without perturbation is 73% in compare to the total power emitted by the laser. Taking in account the power penalty introduced by the different devices present in the optical path it can be shown that the coupling efficiency increases up to 79% in compare to the total power that arrives to the coupling stage. This maximum power value is used as a reference to evaluate the efficiency of the adaptative optic system.

Starting from a non perturbated scenario, a random phase map is introduced into the steering and DM actuators. From this arbitrary state, the SPGD performs the wave-front correction. The SPDG key control parameters are the perturbation size (dQ), which defines the stochastic perturbation magnitude applied by the DM during the blind search, and the loop gain (G), which determines the weight value of the applied correction for each iteration. In Figure 4 the image beam profile is shown for the different stages of the compensation.

In figure 5 the convergence of the SPGD is shown for the an arbitrary perturbation and for different values of dQ and G. Due to the fact that the SPGD is a stochastic process, the graphs represent an averaged measure of ten realizations for the same aberration. In this case, the initial optical power is above the detector sensitivity to ensure that the perturbations applied by the DM have an influence on the measured power for each iteration. This allows us to measure the convergence on the performance metric and evaluate the response for each scenario.

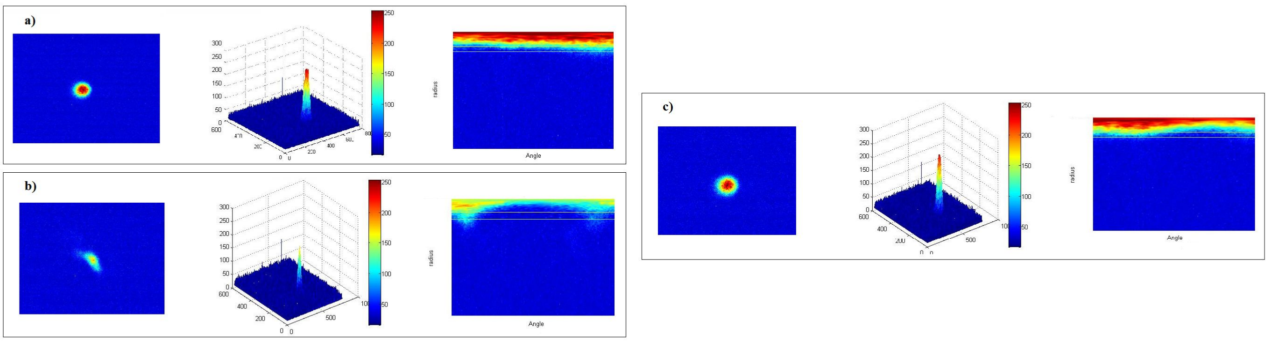
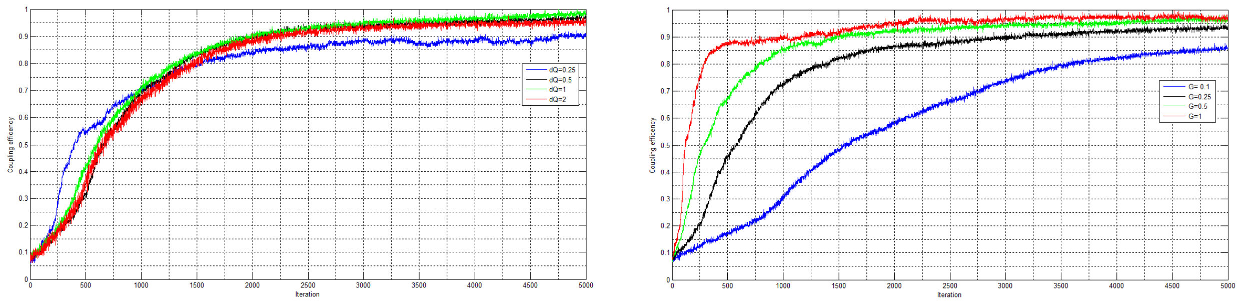


Fig. 4. *Beam image, 3D beam profile and beam profile in polar coordinates for* ***a)*** *Non aberrated beam,* ***b)*** *Aberrated beam by random phase map applied to the DM and* ***c)*** *Corrected beam after 5000 iterations.*

In Fig. 5.a), the adaptative optic correction efficiency observed is close to 0.98 when a perturbation size higher than 0.25V is applied having a gain parameter of 0.5. Under this situation, the convergence of the system has a greater slope at the beginning of the compensation, achieving a correction from 8% to 55% in the first 500 iterations. For higher *dQ* the efficiency is around 35% at that point. Then it slows down and never achieves the optimal correction, staying around efficiency around 90%.

The gain parameter is evaluated in *Fig. 5.b).* Its influence on the performance slope is proven to be critical. When a low gain is applied, the converge of the SPGD slows down. A representative point to evaluate the parameter performance is around the 500 iteration. For a gain parameter of 0.1, the adaptative efficiency has increased from 8% up to 17%. As we increase the gain, the efficiency at this point is around 45%, 67%, and 87% for a gain of 0.25, 0.5 and 1 respectively. In the other hand, the variance of the signal increases with a higher gain, having a value of 0.016, 0.029, 0.044 and 0.061 for gain values of 0.1, 0.25, 0.5 and 1 respectively.



a) b)

Fig. 5. *Adaptative optic Efficency by running the SPGD algorithm for* ***a)*** *Gain of 0.5 and different values of the perturbation size dQ and* ***b)*** *Perturbation size of 0.5 and different values of G.*

5. Conclusions

We have demonstrated the viability and evaluated the efficiency of a practical compact adaptative optical system, which increase the coupling efficiency of an aberrated beam into a single-mode fiber. The performance of the adaptative optic system is highly dependent on two parameters, the perturbation size and the gain control, which define the performance slope of the adaptative system.

An adaptative efficiency above 98% is achieved for different scenarios, which demonstrates the benefits of adaptative optics over the receiver sensitivity.

6. Acknowledgments

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7. References

[1] L. C. Andrews, R. L. Philips, "*Laser beam propagation through random media*". Bellingham, SPIE Press, 2005.

[2] R. K. Tyson, *Introduction to Adaptive Optics*. Bellingham: SPIE Press, 2000.

[3] T. Weyrauch, M. Vorontsov, *"Free-space laser communications with adaptive optics: Atmospheric compensation experiments,"J. Opt. Fiber Comms. Rep. 1, 355-379, 2004.*