Wavefront-sensorless aberration correction of extended objects using a MEMS deformable mirror

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ABSTRACT

The original proposal of wavefront-sensorless aberration correction was suggested by Muller and Buffington[1]. In this technique we attempt to correct for wavefront aberrations without the use of conventional wavefront sensing. We apply commands to a corrective element with adjustable segments in an attempt to maximise a metric which correlates to image quality. We employ search algorithms to find the optimal combination of actuator voltages on a DM to maximise a certain sharpness metric. The "sharpness" is based on intensity measurements taken with a CCD camera. It has been shown [2] that sharpness maximisation, using the simplex algorithm[3], can minimise the aberrations and restore the Airy rings of an imaged point source. This paper demonstrates that the technique can be applied to extended objects which have been aberrated using a Hamamatsu SLM to induce aberrations. The correction achieved using various search algorithms are evaluated and presented.

Keywords: Adaptive Optics, Image Sharpness, Simplex Algorithm

1. INTRODUCTION

In conventional adaptive optics (AO) systems a wavefront corrector such as a deformable mirror (DM) is used to correct for an incoming aberrated wavefront. The necessary corrections that need to be applied to the deformable mirror are determined using a WFS. These corrections are applied to the DM through a control computer. This vast area affected and dependant on adaptive optics stems originally from an AO system proposed by H. Babcock[3]. The corrections to be applied conventionally rely on the use of a WFS which measure the phase, phase gradient or phase curvature directly[4,5,6]. It is shown that wavefront-sensorless correction can be made to aberrated images in a simple regime.

1.1. Wavefront Sensing

There are two main areas of wavefront sensing: direct and indirect wavefront sensing. In direct WFS a wavefront sensor is required to sense the wavefront with high spatial resolution and speed to apply realtime correction. Direct methods provide information about wavefront phase and this information is used to drive a wavefront corrector. Generally direct methods are employed in atmospheric and visions science where correction need to be made at a higher rate.

The wavefront sensor is a fundamental element of most conventional adaptive optics systems. Wavefront measurements need to be fast, and with a high spatial resolution. Real-time corrections, measurement and deformable mirror adaptation have to last less than the typical constant time of atmospheric distortions changes. Direct wavefront sensing methods such as the Shack-Hartmann WFS[4] provide information about the wavefront phase, which is then used drive a wavefront corrector. In this sense, direct wavefront sensors directly measure the wavefront phase from which the necessary correction can be determined.

Indirect techniques do not directly measure implicit or explicit wavefront properties, but use information related to the wavefront to provide the signal for the corrective element without reconstruction. This area of research is based on a "sharpness" criterion, which is used as an image metric to measure the degree of correction of the wavefront phase. The principle of image sharpening can be explained by figure 1, a schematic diagram of image sharpening methods.

The image sharpness metric is a measure of the image quality and in general the higher this metric the better the image quality. In sharpness maximisation a trial phase correction is applied to the image via a corrector and the effect on the sharpness metric is noted. Using a suitable sharpness metric, and a search algorithm which determines the trial phase to be applied to the corrector, the system is driven to maximise the sharpness metric and minimise the aberration.

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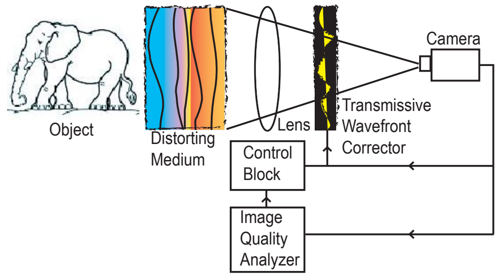

Figure 1. Basic configuration of image sharpness correction system (after Vorontsov[8])

2. IMAGE SHARPNESS PRINCIPLE

The concept of correcting for aberrations in an optics system based on image metrics was first proposed by Muller and Buffington in 1974[1]. This method uses a definition of sharpness of image to minimize aberrations in conjunction with a wavefront correcting medium. This technique was superseded with the advent of modern day WFS such as the Shack-Hartmann due to the speed of correction that they facilitated. However, with the advancement of modern day computers and CCD cameras this method can be applied at a high enough rate to correct for slowly varying or static aberrations.

An image sharpness metric is a measure of image quality and in general the higher the metric the better the image quality. In sharpness maximisation a trial phase correction is applied via a corrector and the effect on sharpness is noted. Using a suitable sharpness metric and a search algorithm, which determines a trial phase to be applied to the wavefront corrector, the system is driven to maximise the sharpness metric and minimise the aberration.

The sharpness maximisation relies on how the sharpness is defined. The problem arises when one quantitatively tries to define the word "sharp". Muller and Buffington define the sharpness such that its value for an aberration-degraded image is always less than that of the true image. In their paper Muller and Buffington set out 8 sharpness metrics. One such sharpness definition is

$$S_1 = \int I^n(x,y)dxdy \quad n = 2, 3, 4, \tag{1}$$

where x, y denote coordinates in the image plane and $I(x, y)$is the image irradiance. This sharpness definition will be maximised when there is zero wavefront error, even in the presence of irregular object radiance distribution. This amplitude insensitivity makes this method useful for large extended objects. Other sharpness functions, such as higher-order moments of distribution, or entropy minimization functions,

$$S_2 = -\int I(x,y)ln[I(x,y)]dxdy, \tag{2}$$

have been examined by Muller and Buffington[1] and are proven to relate to low wavefront error. Numerous papers have since been published detailing further image sharpness metrics[2]. Some metrics which have been developed are object dependant and the metric is chosen based on the scene[7-11]

3. SEARCH ALGORITHMS

Image sharpness maximisation requires the correcting device to be driven to its optimal shape to minimise the aberrations. For a DM with 37 actuators which operate over 255 different voltages this is an unfeasibly large space to search systematically. To search the large range of possible mirror shapes (255^{37}degrees of freedom (DOF)) it is necessary to implement a search algorithm to determine the global minimum(or maximum).

Ideally when using a search algorithm routine the global minimum is the final state i.e. the true minimum of the system. This is very difficult to find for systems having a large number of DOF, due to the probability of falling into a local minimum. Generally, for complicated optimisation problems, non-systematic search routines, such as, the Nelder-Mead simplex, Stochastic Gradient Descent (SGD), Stochastic Parallel Gradient Descent (SPGD), will give the best solution[12].

3.1. The Nelder-Mead Simplex Algorithm

As mentioned above the simplex algorithm is not a systematic search algorithm in the sense that is doesn't search every possible node in the search space, but it does move in a methodical way through the search space.The simplex search method proposed by Nelder and Mead[13] is an algorithm that tries to minimise a scalar-valued nonlinear function of n real variables using only function values. A simplex is a geometrical figure consisting of $n + 1$ vertices, where n is the number of DOF. In two dimensions a simplex would be a triangle, in three, a tetrahedron and in this experiment a complex figure with 38 vertices. Each vertex represents a set of mirror voltages. Initially, 38 ($n + 1$) random sets of voltages are generated and the corresponding sharpness value is measured for each vertex. Based on the initial evaluations the simplex attempts to adapt to the local landscape, with the aim of contracting to the global minimum. This is done through a series of reflections, expansions, contractions and shrink operations. The simplex can be set to run for a certain number of iterations, or to stop when a termination criteria is met.

Although Nelder and Mead published their paper in 1965, no theoretical results regarding convergence properties of the Nelder-Mead method in higher dimensions have yet been proven. Even finding any function in R^2 for which the algorithm would always converge to a minimum still remains and open problem[14]. Therefore, one cannot say with certainty that the maximum sharpness value reached by the simplex is the global maximum.

3.2. Stochastic Gradient Descent Processes

This is an iterative multivariate optimisation search method, first implemented on an adaptive optics system by Vorontsov[15]. Stochastic methods add random processes which aid the algorithm to converge on the global maximum.

In standard gradient descent the true gradient is used to update the actuator voltages. The true gradient is usually the sum of the gradients caused by each individual trial perturbation. The voltages are adjusted by the negative of the true gradient multiplied by a step size. Therefore, standard gradient descent requires one sweep through the training set before any voltages can be changed.

In stochastic parallel gradient descent the true gradient is approximated by the gradient of the cost function only evaluated on a single trial perturbation. The voltages are then adjusted by an amount proportional to this approximate gradient. Therefore, the parameters of the algorithm are updated after each perturbation. For a large number of degrees of freedom stochastic parallel gradient descent is much faster that general gradient descent.

4. EXPERIMENTAL PROCEDURE

4.1. Apparatus

A narrow band Luxeon Star LED, wavelength $635nm$, is used to illuminate a two dimensional extended object. The extended object is imaged onto a Retiga CCD camera via a Hamamatsu Spatial Light Modulator(SLM) and a DM. The SLM generates Zernike aberrations which are created in MATLAB. The aberrations are fed to the SLM via the green component of a RGB cable which is connected to a second graphics card port on the control computer.

The resolution of the Zernike images created in MATLAB are created to match the pixel dimensions of the SLM which is 1024 x 768. The SLM can create a 2π phase change and the phase can be wrapped in the MATLAB program to place stronger aberrations in the system.

The deformable mirror is a 37-channel OKO MEMS mirror[18] with a diameter of $15mm$ and has a frequency range of up to 1 KHz. The device can be used for fast dynamic correction of low-order optical aberrations such as defocus, astigmatism, coma, etc. The mirror is operated over a range of 0 to 255 V. The experimental set-up can be seen below in figure 2.

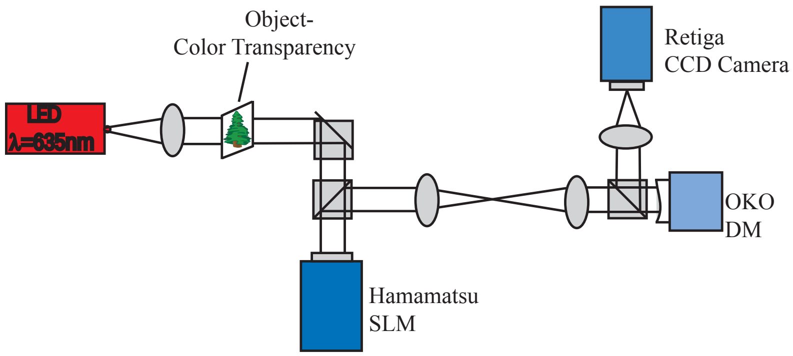

Figure 2. Experimental set-up.

4.2. SLM Aberration Generation

The MATLAB program was written to create any combination of Zernikes. These aberrations could be 'dialled up' and placed onto the SLM. The phase change created by placing Zernike patterns on the SLM was measured using a Fisba interferometer and two typical aberrations can be seen in figure 3. The images to be corrected were distorted with a combination of defocus and astigmatism. The magnitude of these two aberrations was not fully calibrated over the image plane and the image is further disturbed by system aberrations.

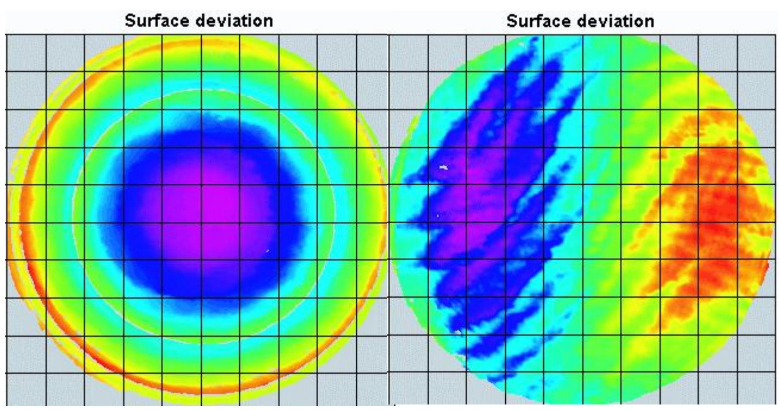

Figure 3. Example of Zernike aberrations generated on SLM, defocus(left 1.5λ P-V) and coma(0.5 λP-V).

4.3. Experimental Process

With the experimental set-up described above, the power law metric (eq:1) described by Muller and Buffington was examined. This metric was shown to relate low wavefront aberration to an increased sharpness value for extended objects[1].

Various combinations of Zernike aberrations were generated and each algorithm was run to correct for the aberrations. The algorithms were tested to maximise the S_1 (eq : 1) sharpness metric for a combination algorithms. The algorithms were also used to test the limit of correction system. This was determined by placing an aberration in the system, running the algorithm to correct for the aberration and subsequently increasing the aberration until the DM/algorithm could not find any corrected solution. In this sense the limitation of correction could be a limitation of either the algorithm or the physical limits of the DM deformation.

5. RESULTS

To compare the correction of aberrated extended images a USA AF target image was used. This enabled a profile to be taken through aberrated and corrected images. The results of correction of an aberrated, aberrated and corrected target image can be seen below in figure 4.

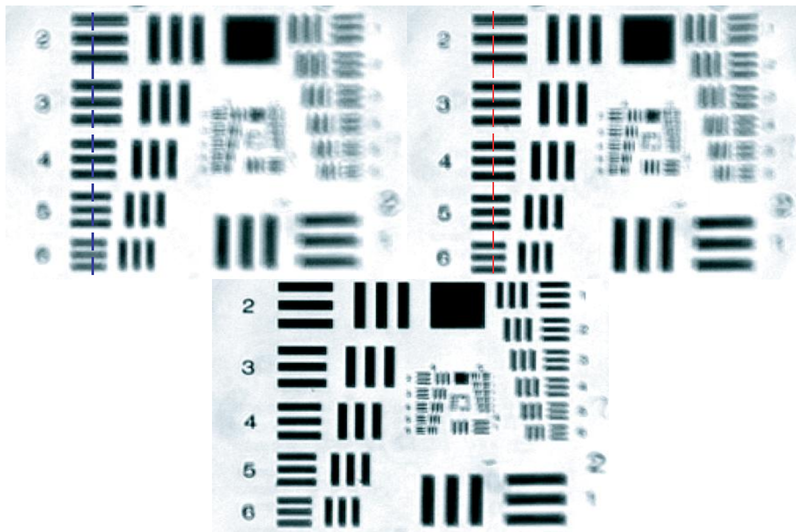

Figure 4. Example of correction achieved with the simplex algorithm with the aberrated image top left, corrected image(1000 iterations of the simplex) top right and unaberrated image bottom.

As can be seen there is a significant degree of correction to the aberrated target image. The central bar targets in the image can be resolved better and more detail is present. However, it is clear that the correction is not perfect. It could be the case that simplex algorithm fell into a local minimum or that the aberration was too much for the mirror to correct for, that is, the limited stroke of the mirror can't take the necessary conjugate shape for full correction.

To demonstrate that the image is sharpened and the aberration reduced, a profile is taken through two sections of the target image and the profiles are plotted together, as seen in figure 5.

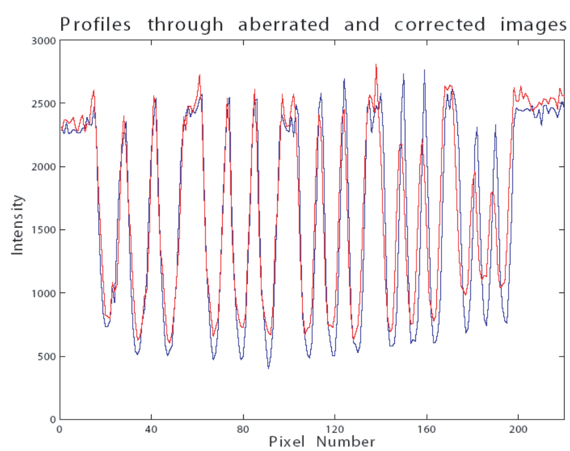

Figure 5. Profiles taken through corrected and uncorrected target images.

It can be seen that the corrected image has much more contrast through the profile. This corresponds to a reduction of the aberrations and an increase in the image sharpness.

The SPGD algorithm was also tested with the same extended object and aberrations and the results shown in figures 6 and 7.

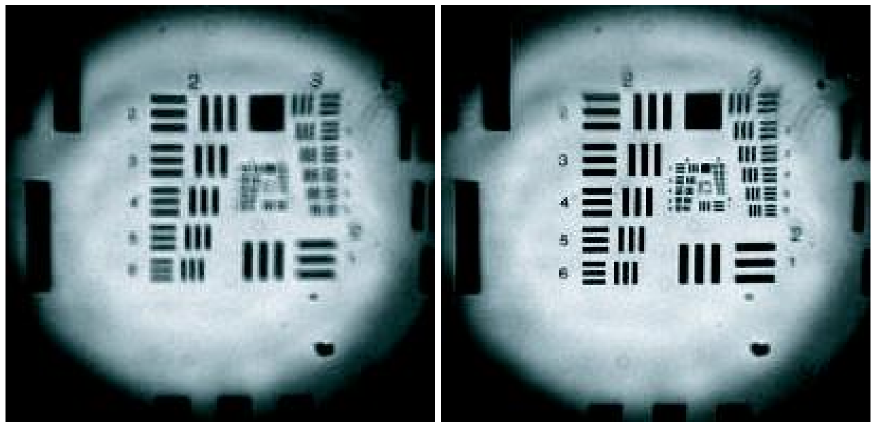

Figure 6. Aberrated and corrected image resulting from SPGD algorithm correction.

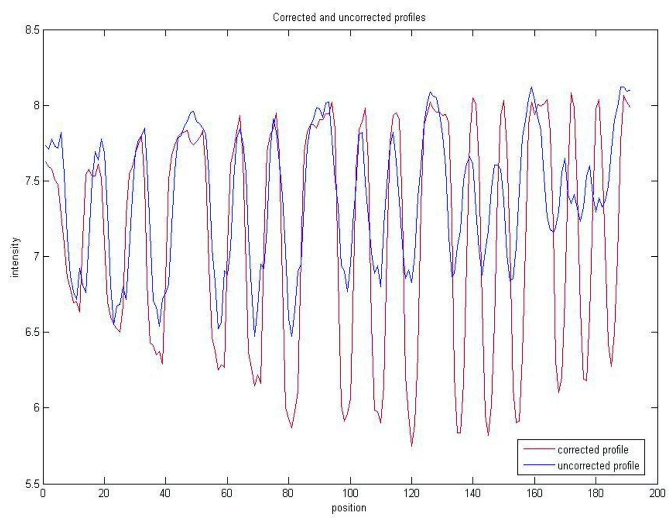

Figure 7. Profiles taken through aberrated and corrected images for SPGD algorithm.

It can be seen from the profiles taken through the target images that increasing the sharpness increases the contrast of the image.

To demonstrate that sharpness maximisation can correct for extended object of varying types the SPGD algorithm was used to correct for an aberrated image of a building and can be seen in figure 8. The increased clarity of the writing on the building demonstrates that by maximising the sharpness an aberrated image can be corrected.

Figure 8. Shows aberrated and corrected images from university building.

6. CONCLUSIONS

As mentioned above each algorithm was tested for the S_1 metric for $n = 2$. Preliminary tests were carried out for n=3, n=4 but little difference was noted in the performance of the metrics. Further analysis is needed to determine the performance of these metrics. There are several other sharpness metrics[1] that can be applied to extended objects and these too should be tested to determine which sharpness metric performs best and for what object base.

The power-law metrics set out by Muller and Buffington have been shown to produce good correction for a point source image[2]. This paper shows that the power law metrics can also be applied to extended objects to minimise aberrations.

It has been shown that the power-law metrics can be used to "blindly" correct for small aberrations in an indirect wavefront sensing system, or, act as a wavefront-sensor less correction. Each of the algorithms tested produced good correction to images aberrated by a combination of defocus and astigmatism. They have potential to correct for a combination of Zernike aberrations introduced into the system - to the limit of the deformable mirror. Further analysis needs to be made to test the algorithms and the deformable mirror to the limit of their correction.

The SPGD and SGD algorithms were found to achieve the best degree of correction. Further analysis of the search space for aberrations is needed. Better understanding of the nature of the image search space for different scenes and aberrations will aid the choice of correcting search algorithm.

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