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# Wavefront coding with adaptive optics

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**Abstract.** We have implemented an extended depth of field optical system by wavefront coding with a micromachined membrane deformable mirror. This approach provides a versatile extension to standard wavefront coding based on fixed phase mask. First experimental results validate the feasibility of the use of adaptive optics for variable depth wavefront coding in imaging optical systems.

**Keywords:** Depth of Field, Wavefront Coding, Deformable Mirror, Imaging, Adaptive Optics. **Address all correspondence to**: Temitope E.Agbana, TU Delft, Faculty 3ME, DCSC, Mekelweg 2, 2628CD Delft, The Netherlands; Tel: +31(0)-15-2785305; Fax: +31(0)-15-2786679; E-mail: t.e.agbana@tudelft.nl

## 1. Introduction

Depth of field (DOF) is a major performance characteristic of any imaging system. The deeper the field, the more information about the object can be obtained with a single image. Any imaging system realizes a compromise between the DOF, the light collecting ability and the image signal to noise ratio (SNR). The DOF is reduced as the numerical aperture (NA) and the resolution of the imaging system is increased.[1] Especially in high-resolution microscopes with large NA, the DOF is limited.[2,3] An effective solution for the problem DOF control is, therefore, of interest for general design of imaging systems, regardless the application.

Control of the DOF has been an active research topic for many years. A conventional method of extending the DOF involves stopping the lens, and — in a more sophisticated approach — manipulating the pupil function by inserting shade masks or apodizers.[4,5] This method increases the DOF at the expense of light power at the image plane, lower resolution and reduced SNR. The use of axicons is another technique used for increasing the DOF.[6] This technique is usable mostly for on-axis images, as a wider field of view suffers from strong aberrations. Hausler *et al*[7] proposed a method which involves a continuous change in focus during the exposure time, superimposing the modulation transfer function for different foci in a single image. This technique produces a depth invariant point spread function (PSF), but it requires the use of quick controllable focus change. Spectral focal sweep[8] alleviates the problem of moving parts by exploiting the chromatic aberration. The efficiency of this approach depends on the illumination and reflection spectra of objects being imaged. Objects that are not sufficiently broadband cannot produce a large spectral focus range. Taking multiple images at different focus level and synthesizing them via image fusion was also proposed for DOF extension.[9]

Finally, a distinct method for extending the DOF was proposed by Dowski and Cathey.[10–12] This technique called 'Wavefront coding' involves the use of cubic phase plate at the pupil plane, to form and store intermediate coded images. Digital processing is then used to restore the coded images. It is

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an hybrid optical/digital technique that reduces the system complexity, improves imaging capabilities and provides a good performance.[13]

## 2. Basics of wavefront coding

A family of cubic phase pupil functions produce defocus-invariant PSFs.[10,14–16] Usually these functions are implemented with cubic phase plates. The cubic phase plates introduce a two-dimensional phase delay[15,16] as a function of spatial coordinates, described by:

$$P(x,y) = a_{3,0}x^3 + a_{2,1}x^2y + a_{1,2}xy^2 + a_{0,3}y^3 \tag{1}$$

where the coefficients $a_{i,j}$ define the form and the amplitude of the pupil function. The DOF achievable by the coded imaging system is directly proportional to the strength of the phase element. Since the implementation of the optical system could be based on diverse application and different circumstances, the requirements to the wavelengths, NA, required DOF and the resolution of the imaging system could also vary. With this variation in application, it is extremely useful to find a dynamic method to control the cubic phase in real time. In this paper we investigate wavefront coding with adaptive optics.

Adaptive optics allows for quick switching between zero pupil modulation, corresponding to an ideal optical system, to dynamically controlled extended DOF system with cubic element in the pupil. This approach provides a flexible *ad hoc* DOF extension.

The intensity pattern $u_i(x,y)$ in an image plane at distance $z$ from the pupil can be described as a convolution of the object intensity $u_o(x,y)$ and the corresponding incoherent point spread function[17,18] $h(x,y,z)$:

$$u_i(x,y) = u_o(x,y) * h(x,y). \tag{2}$$

For a mis-focused optical system, the shape of PSF depends on the defocus amount $W_{2,0}$:

$$h(x,y) \propto \left| \int\limits_{A\neq 0} \mathrm{e}^{\mathrm{i}kA(\xi,\eta)}\, \mathrm{e}^{\mathrm{i}kW_{2,0}(\xi^2+\eta^2)}\, \mathrm{e}^{\mathrm{i}\frac{k}{z}(x\xi+y\eta)}\, \mathrm{d}\xi \mathrm{d}\eta \right|^2, \tag{3}$$

where $A(\xi,\eta)$ is the pupil function, $\xi,\eta$ are the coordinates in the exit pupil, $W_{2,0}$ is the defocus parameter, and $k$ is the wave number.

Implementing wavefront coding techniques implies adding a phase element with a cubic phase function to the exit pupil of the optical system. The PSF of a wavefront-coded aberration free optical system can be written as:

$$h_c(x,y) \propto \left| \int\limits_{A\neq 0} \mathrm{e}^{\mathrm{i}kA(\xi,\eta)}\, \mathrm{e}^{\mathrm{i}kW_{2,0}(\xi^2+\eta^2)}\, \mathrm{e}^{\mathrm{i}kP(\xi,\eta)}\, \mathrm{e}^{\mathrm{i}\frac{k}{z}(x\xi+y\eta)}\, \mathrm{d}\xi \mathrm{d}\eta \right|^2, \tag{4}$$

where $P(\xi, \eta)$ is given by Eq. (1). With a careful choice of coefficients $a_{i,j}$, the obtained PSF $h_c$ is approximately invariant for a range of defocus values $W_{2,0}$ (with PSF shifts depending on the defocus).[10,14,15] Thus the coded images

$$u_c(x, y) = u_o(x, y) * h_c(x, y) \tag{5}$$

are also little dependent on the defocus value, and can be deconvolved using defocus-independent Wiener filter:[19,20]

$$W(\xi, \eta) = \frac{H_c^*(\xi, \eta)}{|H_c(\xi, \eta)|^2 + C}, \tag{6}$$

where $H_c = \mathcal{F} h_c$ is the Fourier transform of the coded PSF and $C$ is a parameter related to the image SNR, which is interactively adjusted to provide a good reconstruction result. To obtain the recosntructed image, an inverse Fourier transform operation $\mathcal{F}^{-1}$ must be performed on the filtered image:

$$\mathcal{F}^{-1}[U_c(\xi, \eta) \cdot W(\xi, \eta)] \tag{7}$$

where $U_c(\xi, \eta)$ is the Fourier transform of $u_c(x, y)$.

## 3. Experiment

An experimental setup shown in Fig. 1 has been developed to validate the proposed methodology. Low-cost 15-mm 19-ch (17 deformable modes plus tip-tilt) Micromachined Membrane Deformable Mirror (MMDM) from OKO Tech, Delft, the Netherlands was used as the adaptive phase element. This device can be used for fast dynamic correction of low-order optical aberrations such as defocus, astigmatism, coma, trefoil etc.[21]

Light from a single-mode fiber ($\lambda = 632nm$) is collimated by lens L1 with focal length of 100 mm, to a beam of 8 mm in diameter. The telescope formed by lenses L2 and L3 with focal lengths of 80 mm and 100 mm re-images the system pupil, scaling it to the diameter of 10 mm, centered on the MMDM. The beam reflected from the MMDM is split into two arms: one towards the imaging camera and the other one to the wavefront sensor. Relay optics formed with L5 and L6 conjugates the Shack Hartmaan WFS with the system pupil and the deformable mirror, while the lens L4 focuses the beam to the CCD.

The control includes two closed loop system:

1. to enable the adaptive compensation of the aberrations in the optical system, including the non-common path aberration;

2. to control the deformable mirror, for extended DOF WF coding.

The adaptive system was calibrated and run in the following order:

- At the first stage the Nelder-Mead simplex optimisation algorithm was used to control the MMDM shape, to minimize the spot size of the focused image of the single-mode fiber tip on the CCD. As a result of this optimization, with the help of a deformable mirror, we obtained a virtually aberration free optical system that imaged the fiber tip plane to the CCD plane.

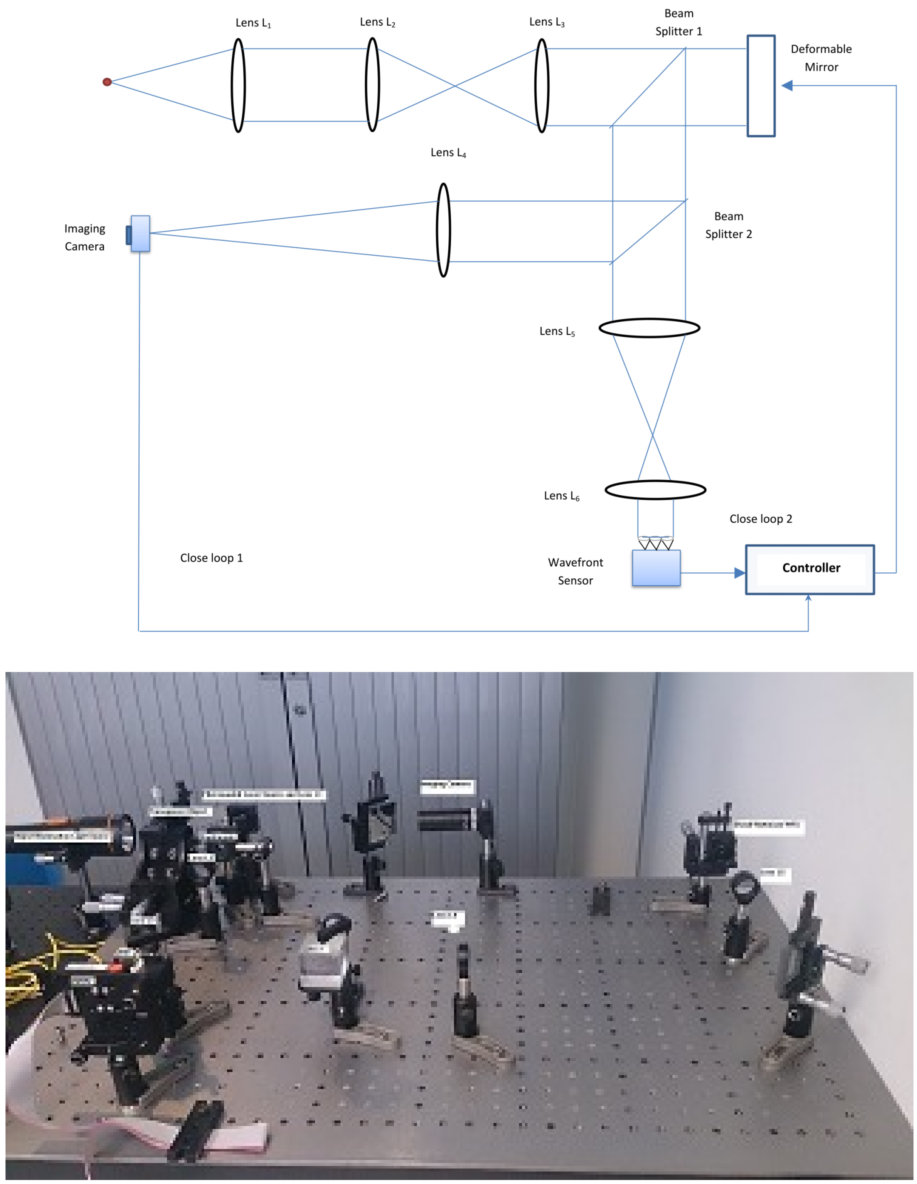
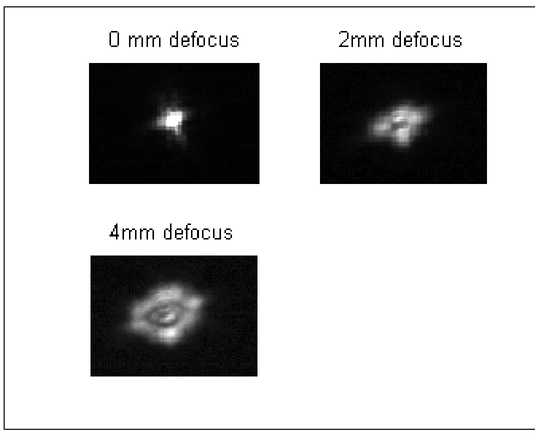


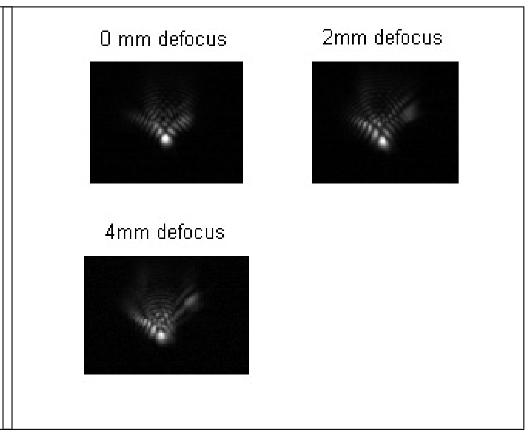

*Fig 1: The configuration of the optical system.*

- A reference pattern was registered in the Shack-Hartmann sensor, that corresponds to the aberration free system. Starting from this system state, the FrontSurfer software (OKO Tech, Delft, the Netherlands) was used for the calibration of the MMDM. The FrontSurfer uses a set of measured influence functions of the mirror for fitting of the desired phase aberration.[21] This aberration, defined as a combination of Zernike polynomials[22] can be manually controlled by feeding the weights of Zernike terms to the adaptive feedback loop. To create a cubic phase function, a combination of two 3rd-order Zernike terms (coma+trefoil) was formed by the DM in the system pupil. The strength of this target function can be dynamically controlled, however we found that the maximum amplitude of the cubic function is limited by the DM deformation range.

- After the desired PSF was obtained, it was registered by the CCD. A special care was taken to register the PSF at the linear shoulder of the CCD response, avoiding oversaturation that would cause information loss at the reconstruction phase.
- In the calibrated system with coded pupil, a transparency showing a house tower was used as an object. The object was illuminated with extended incoherent white LED source.
- A number of images of both the PSF and the object have been registered for different in and out of focus positions for ideal optical system and for the coded system. Fig. 2 shows the recorded experimental PSF of our conventional and coded imaging system.




*(a) Conventional PSF*



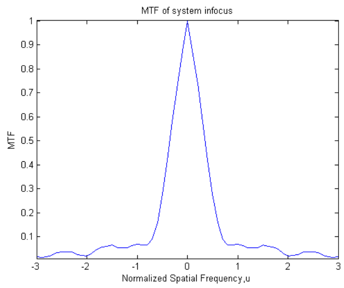

*(b) Coded PSF*

*Fig 2: Experimental PSFs. The cubic function formed by the MMDM has maximum amplitude of* $1\lambda$.

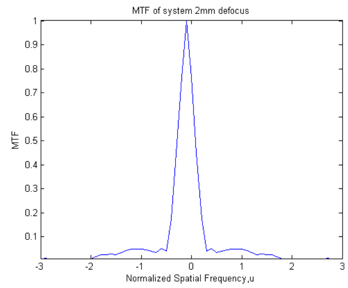
The MTFs, estimated from the measured PSFs are depicted in Fig. 3 and 4 respectively. Fig. 3 shows that as the conventional system becomes more and more defocused, the size of the PSF increases causing loss of the high frequency terms in the image. With the coded system, the invariance of the MTFs at higher spatial frequencies decreases only slightly, and digital restoration of the image with simple filtering is possible. The restoration process operates on the coded MTF with the goal to retrieve the diffraction limited features of the image. Comparing the convetional system to the coded one, it can be observed that defocus alleviation by the coded system results in increase of the DOF. When the defocus is increased beyond a certain limit, coding cannot provide sufficient invariance. This limits the performance of the coded MTF resulting to loss of spatial resolution on the restored image. For visual illustration, our object was imaged with the conventional imaging system and the coded imaging sytem.

The coded images are subsequently restored and the results are shown in Fig. 5 and 7. Fig 5(a) shows the recorded image in focus. Moving the object through a defocus range of 4mm in steps of 2mm proudced blurry images shown in Fig. 5(b) and (c). Coded image recorded under similar conditions are depicted in Fig. 6. All coded images are restored using the in-focus cubic PSF and

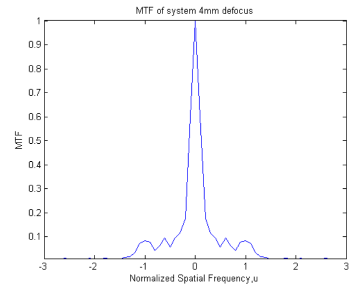
Wiener filtering. The restored images are presented in Figure 7. The DOF extension is clearly visible, in spite of limited range of cubic function that could be created with MMDM.




*(a) Infocus position*

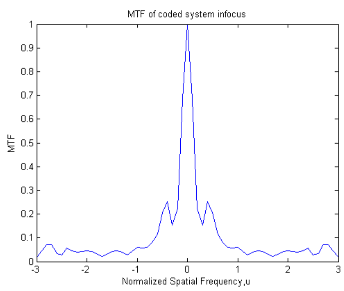



*(b) 2mm out of focus*

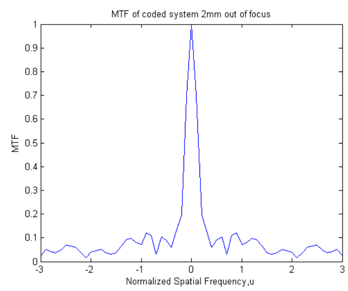



*(c) 4mm out of focus*

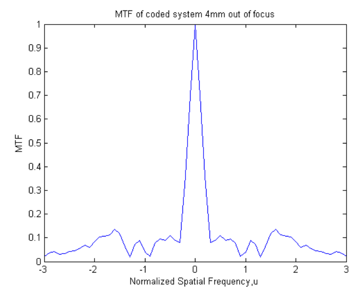
*Fig 3: Modulation Transfer Functions for three focus positions in aberration-free optical system.*




*(a) In-focus .*

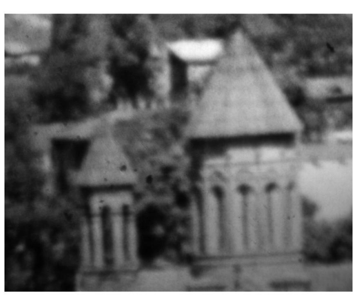



*(b) 2mm defocused*




*(c) 4mm defocused*

*Fig 4: Modulation Transfer Function from a dynamic cubic phase element focus-invariant sytem*



*(a) Image in-focus*

*(b) Image 2mm defocused*

*(c) Image 4mm defocused*

*Fig 5: Recorded Images with Conventional imaging system*

*(a) In-focus coded image.*

*(b) Defocused @ 2mm*

*(c) Defocused @ 4mm*

*Fig 6: Intermediate coded images*

*(a) Restored Image in-focus*

*(b) Restored image@2mm*

*(c) Restored image@4mm*

*Fig 7: Restored Images with signal processing*

## 4. Conclusion and future work

The experiment proves that a deformable mirror in an imaging optical system is not only efficient in improving the dynamic image quality and correcting the system aberrations, but it also can be used for static and dynamic wavefront coding by forming a pre-defined phase mask in the system pupil.

Images obtained with extended DOF demonstrate the applicability and the usability of the method. The DOF range can be further extended by using a deformable mirror with larger deformation range and higher precision of cubic correction, compared to the low-cost 19-ch MMDM. The design of such a special deformable mirror can be based on the common principles of design of high-precision low-order deformable mirrors with smooth surface, outlined in.[23]

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