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# Feedforward Operation of a Lens Setup for Large Defocus and Astigmatism Correction

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## ABSTRACT

In this manuscript, we present a lens setup for large defocus and astigmatism correction. A deformable defocus lens and two rotational cylindrical lenses are used to control the defocus and astigmatism. The setup is calibrated using a simple model that allows the calculation of the lens inputs so that a desired defocus and astigmatism are actuated on the eye. The setup is tested by determining the feedforward prediction error, imaging a resolution target, and removing introduced aberrations.

**Keywords:** Active or Adaptive Optics, Imaging

## 1. INTRODUCTION

The resolution of many optical imaging techniques is hampered by optical wavefront aberrations. Some eye diseases can lead to blindness, hence it is important to detect these eye diseases as early as possible. Better image quality of the retina could result in earlier detection and diagnosis of several eye diseases. In case of retinal imaging, the cornea and the eye lens introduce the largest wavefront aberrations and reduce the resolution and image quality of retinal images. The main three aberrations in the human eye are the lower order aberrations: defocus, and oblique and vertical astigmatism,<sup>1</sup> but higher order aberrations are present in the eye as well. In the normal population of healthy eyes<sup>1</sup> the lower order aberrations in the eye varied from -12 to 6 diopters for the defocus, from -1 to 1 diopters for the oblique astigmatism and from -1 to 2 diopters for the vertical astigmatism.

Current adaptive optics systems<sup>2</sup> can correct relatively small higher order aberrations and large lower order aberrations. However, the combination of large amplitude lower order aberrations in combination with low amplitude high order aberrations requires adaptive optics with a large number of actuators and large stroke. Hence, the extra cost of adaptive optics becomes significant, but can be reduced by using adaptive lenses.<sup>3,4</sup>

In Villegas et al.<sup>3</sup> an optical lens setup is described to correct astigmatism with two rotational cylindrical lenses. It is shown that the astigmatism can be removed using the rotational cylindrical lenses and a lens on a translation stage is used to remove the defocus. The feedforward calibration of such a setup is not mentioned. In Ref. 4 a setup with two low cost rotational lenses is also used for astigmatism correction. This setup has been tested in a fundus imaging device, but has no active defocus correction. They also describe how the angles of the rotational lenses can be related to the astigmatism aberration size. In this paper we present the feedforward calibration of an optical lens setup to correct both large defocus and astigmatism and discuss the difficulties faced with the propagation of astigmatism and defocus in an optical setup. A deformable defocus lens and two rotational cylindrical lenses are used to control the defocus and two astigmatism. With feedforward calibration,

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a desired defocus and astigmatism within the range of the lens system can be displayed at the eye without any feedback signals such as wavefront sensor. The goal is to find the inputs of the lenses when the desired defocus and astigmatism to correct aberrations of the patients eye are given. This idea is similar to the feedforward or open-loop calibration of deformable mirrors, where the voltages are mapped to the displacements or aberrations. Alternatively, the proposed method can be used to determine the aberrations in the patients eye using subjective and/or objective feedback of the quality of an image. Once the optimal subjective or objective image quality is reached, the inputs of the lens can be used to determine the aberrations.

We calibrate our lens-based system with a Shack-Hartmann (SH) wavefront sensor. The measured data from the SH sensor is subsequently used to fit an theoretical mapping from the current and angles of the lenses to the defocus and astigmatism aberrations. This allows a simple conversion between the currents and angles of the lenses to the defocus and astigmatism projected on the eye, and vice versa. Furthermore, we image a resolution target to determine the image quality and imaging resolution. The accuracy of the calibration is tested by using lenses with various defocus and astigmatisms. The residual wavefront error is determined with the SH wavefront sensor.

## 2. MATERIALS AND METHODS

The optical design for defocus and astigmatism correction is depicted in Fig. 1. A collimated beam enters the system. For defocus correction a deformable defocus lens (Optotune EL-10-30) is used with a focal power range from about 16 to 50 diopters. An offset lens is in place, which ensures that without the cylindrical lenses the beam size at the eye is the same as the beam size at the deformable defocus lens.<sup>5</sup> The rotational cylindrical lenses

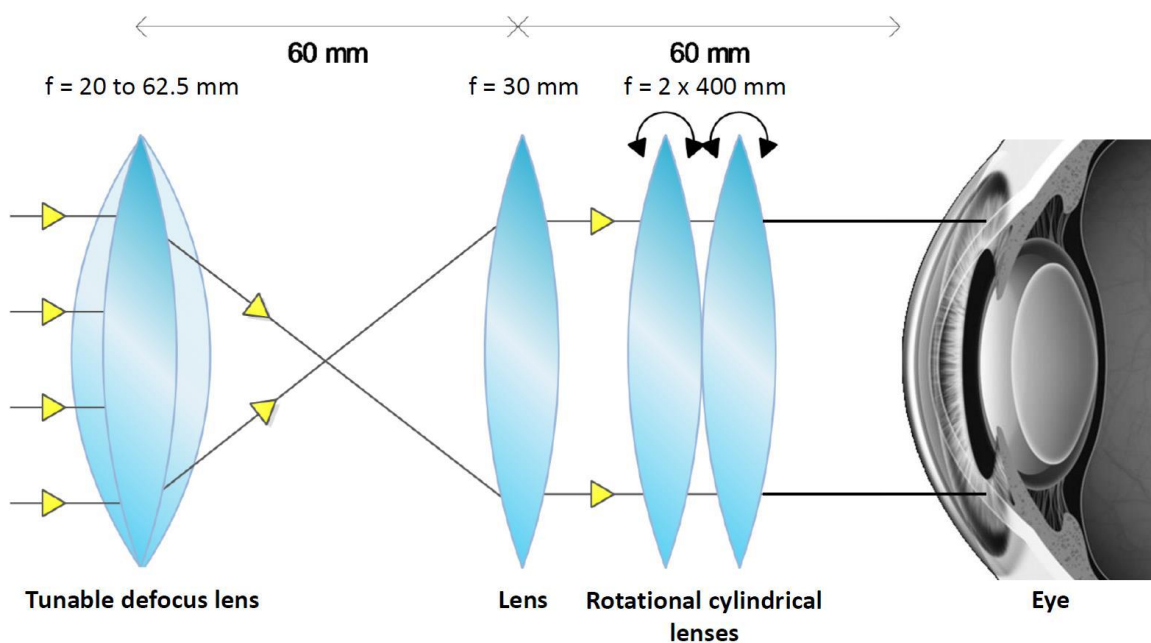


Figure 1. Defocus and astigmatism correction lens setup .

are placed after the offset lens and introduce the astigmatisms. In practice the beam size changes moderately when changing the defocus of the deformable lens with the cylindrical lenses in place.

We calibrated the correction setup with the system shown in Fig. 2 with a Shack-Hartmann sensor. The measured data from the Shack-Hartmann wavefront sensor is subsequently used to fit a theoretical model on the defocus and astigmatism aberrations, which allows determining the corresponding input current of the deformable defocus lens and the angles of the cylindrical lenses. The system shown in Fig. 2 also allows imaging of an object, in this case an illuminated resolution target.

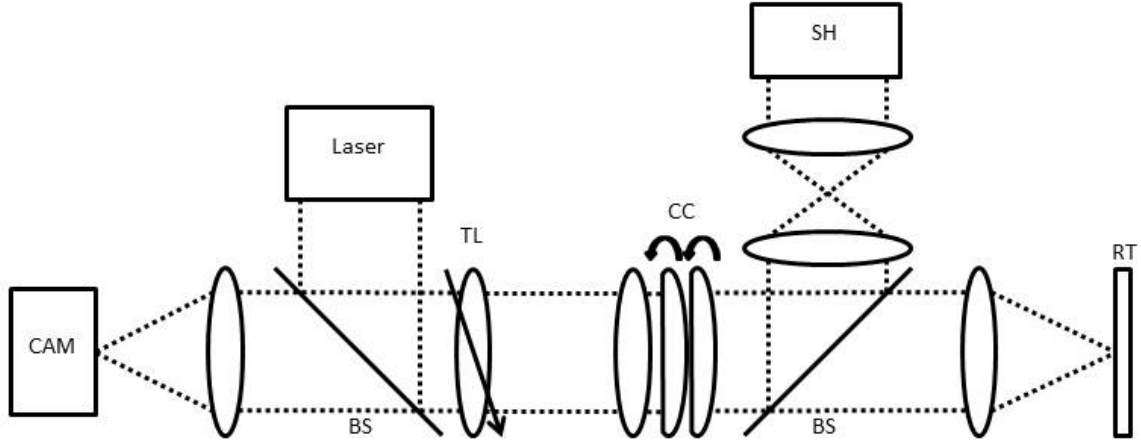


Figure 2. Full lens setup for defocus and astigmatism correction. CAM is the camera, BS are beamsplitters, TL is the deformable lens, CC are the rotational cylindrical lenses, SH is the Shack-Hartmann wavefront sensor, RT is the resolution target.

## 2.1 Fitting the Model

The following equations describe the introduced defocus,  $M$ , and astigmatisms,  $J_0$  and  $J_{45}$ , by two rotational thin identical cylindrical lenses given the angles of the lenses ( $\alpha$  and  $\beta$ ) and the cylindrical power  $C$  of each lens.<sup>6</sup>

$$M = C \quad (1)$$

$$J_0 = -\frac{C}{2} [\cos(2\alpha) + \cos(2\beta)] \quad (2)$$

$$J_{45} = -\frac{C}{2} [\sin(2\alpha) + \sin(2\beta)] \quad (3)$$

In Ref. 7 it was shown analytically that astigmatism and defocus are non-linearly related to the defocus and astigmatism after propagation (to the eye) over a certain distance. In this setup the change in defocus caused by the astigmatism after propagation was small and we neglect its influence. It should be noted that this can be taken into account by making the defocus at the eye dependent on the angles of the 2 cylindrical lenses. However, a change in defocus at the deformable lens influences the astigmatism values at the eye (after propagation) more drastically. To minimize the model fitting error, we express the defocus  $M$  and astigmatism,  $J_0$  and  $J_{45}$ , after propagation at the eye in terms of  $I$ , the current of the deformable defocus lens.

$$M = D(I) \quad (4)$$

$$J_0 = -\frac{A(I)}{2} [\cos(2\alpha) + \cos(2\beta)] \quad (5)$$

$$J_{45} = -\frac{A(I)}{2} [\sin(2\alpha) + \sin(2\beta)] \quad (6)$$

The amplitude  $A(I)$  of the astigmatism is dependent on the current  $I$  of the deformable lens, which determines the defocus. The defocus after propagation at the eye  $M = D(I)$  and the amplitude  $A(I)$  of the astigmatism  $J_0$  and  $J_{45}$  after propagation are fit with two different polynomials. The polynomials are found by minimizing the following problems

$$\min_{d_i, i=0,1,\dots,n} \|\bar{M} - D(\bar{I})\|_2^2 \quad \text{s.t. } D(I) = d_0 + d_1 I + \dots + d_n I. \wedge n \quad (7)$$

$$\min_{a_i, i=0,1,\dots,n} \|\tilde{J}_{0|45} - A(\tilde{I})\|_2^2 \quad \text{s.t. } A(I) = a_0 + a_1 I + \dots + a_n I. \wedge n. \quad (8)$$

Here,  $\cdot \wedge$  is an element-wise power operation on all elements in the vector  $I$ . The data sets of the current of the deformable lens  $\bar{I}$  and the defocus  $\bar{M}$  measured by the SH sensor are obtained for different input currents. The other data sets  $\tilde{J}_{0|45}$  and  $\tilde{M}$  are taken by maximizing one astigmatism and measuring only this astigmatism for different input currents and repeating the same procedure for the other astigmatism. The measurements of the two astigmatisms and their corresponding input currents are then gathered in the vectors  $\tilde{J}_{0|45}$  and  $\tilde{M}$ . In practice, when  $J_0$  is maximized on the SH sensor by rotating the cylindrical lenses, you have removed any undesired offset from  $\alpha = 0$  and  $\beta = 0$ . To also include the dependency of the defocus on the astigmatisms introduced by the cylindrical lenses one could consider fitting a function with three inputs  $M = D(I, \alpha, \beta)$ .

## 2.2 Using the Model for Prediction

Once the model is obtained, it can be used to estimate the defocus and astigmatism aberrations from the input current and angles from the lenses. However, it can also be used to determine the corresponding inputs when a desired aberration is given. Figure 3 show a schematic representation how to derive the inputs the lenses based on the desired aberrations. The input current  $I$  for the desired defocus  $\hat{M}$  can easily be found by minimizing the following minimization problem:

$$\hat{I} = \underset{I}{\operatorname{argmin}} \|\hat{M} - D(I)\|_2^2. \quad (9)$$

When the desired current  $\hat{I}$  is found, the amplitude of the astigmatisms  $A(\hat{I})$  can be calculated and used to find the desired angles  $\hat{\alpha}$  and  $\hat{\beta}$  of the cylindrical lenses. This can be done solving the following minimization problem

$$[\hat{\alpha}, \hat{\beta}] = \underset{[\alpha, \beta]}{\operatorname{argmin}} \left\| \begin{array}{l} \hat{J}_0 + \frac{A(\hat{I})}{2} [\cos(2\alpha) + \cos(2\beta)] \\ \hat{J}_{45} + \frac{A(\hat{I})}{2} [\sin(2\alpha) + \sin(2\beta)] \end{array} \right\|_2^2, \quad (10)$$

where  $\hat{J}_0$  and  $\hat{J}_{45}$  are the desired astigmatisms.

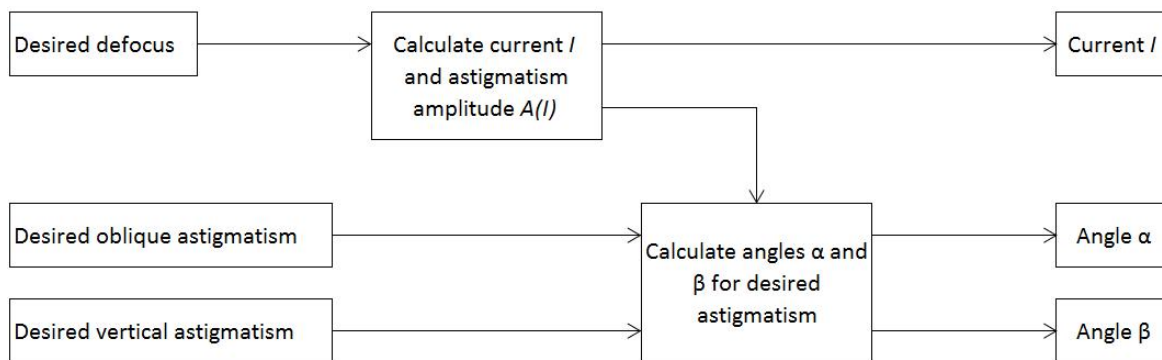


Figure 3. Schematic representation for deriving the inputs of the lens setup when desired aberrations are given.

## 3. RESULTS

To determine the performance of the system three test were performed. First, we test the prediction error by providing 25 different combinations of defocus and two astigmatisms as desired aberrations. The corresponding inputs of these desired aberrations were calculated as described in Eqs. (9) and (10). The SH sensor measures the aberrations obtained from the corresponding inputs and compares the measured aberrations with the desired aberrations. When comparing the measured astigmatisms with the desired astigmatisms the root mean square (RMS) error is 0.075 diopters. The root mean square (RMS) error is 0.17 diopters when comparing the measured defocus with the desired defocus. The desired inputs ranged from -6 to 4 diopters for the defocus, and from -1.5 up to 1.5 diopters for both the astigmatisms.

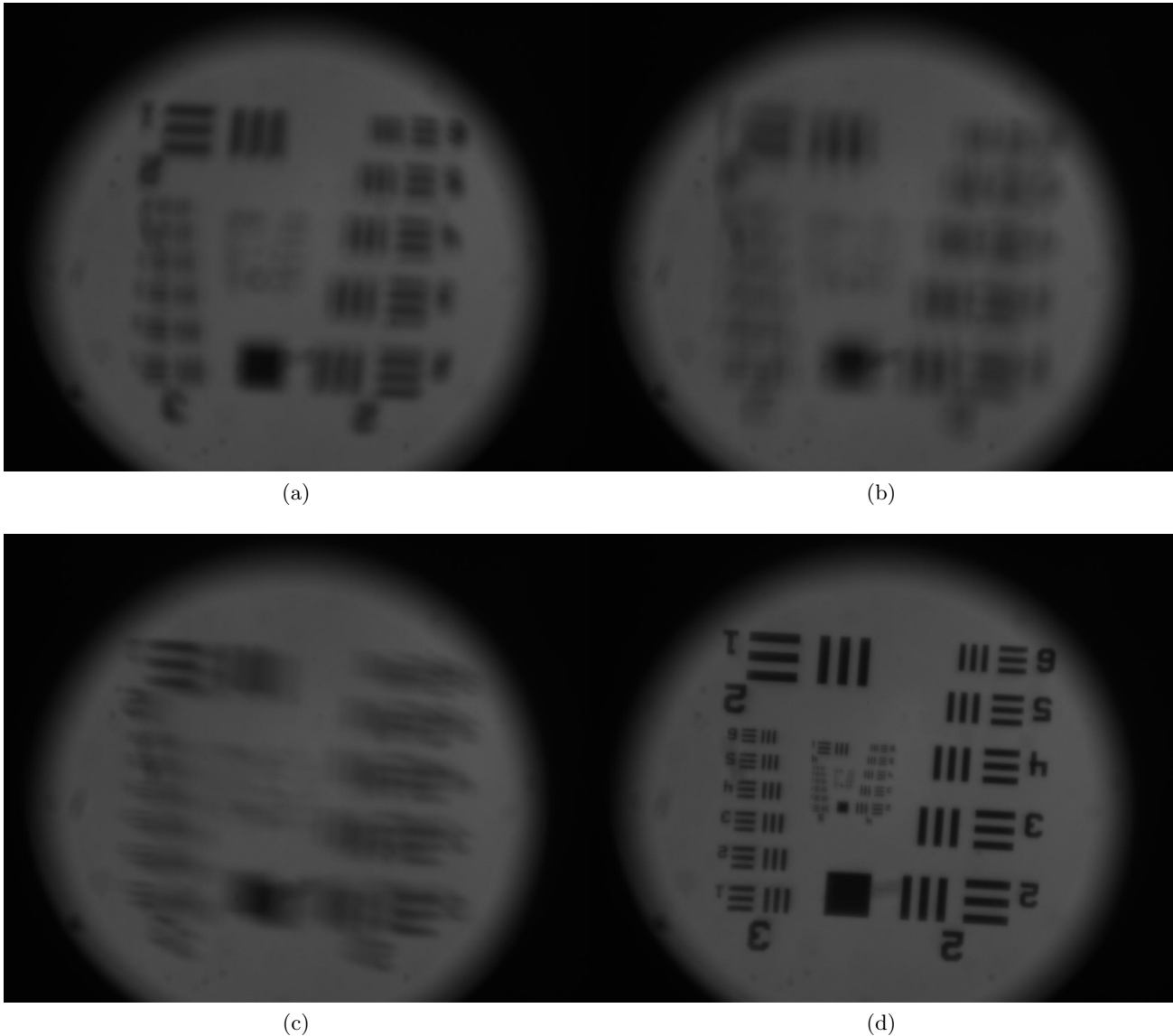


Figure 4. (a) Image with defocus. (b) Image with astigmatism. (c) Image with defocus and astigmatism. (d) Image with aberrations removed.

Secondly, we tested the image quality of the setup by imaging the resolution target shown in Fig. 4. The size of the defocus in Fig. 4(a) is 0.39 diopters. The sizes of the astigmatism in Fig. 4(b) are 0.33 diopters and 0.44 diopters. The sizes of the defocus and astigmatism in Fig. 4(c) are 0.61 diopters, 0.27 diopters and 0.19 diopters.

Thirdly, three different lenses were used to introduce aberrations. A lens with a defocus power of 2 diopters, a cylindrical lens with a power of 0.75 diopters and one cylindrical lens of 0.5 diopters. These aberrations were then measured by the SH wavefront sensor and their negatives were used as a desired aberration for which the inputs were calculated using Eqs. (9) and (10). After applying the obtained inputs, the remaining error for the defocus was below 0.1 diopters and for the astigmatism below 0.05 diopters.

## 4. DISCUSSION AND CONCLUSION

Using simple polynomial fits and small scale optimization problems, we have successfully calibrated a lens setup for feedforward correction of large defocus and astigmatism aberrations. In the current setup the deformable defocus lens suffered from a (temperature drift, which was the main source of the final prediction error. The consistency of the defocus lens was hampered by this drift and introduced errors bigger than the model fit. Furthermore, minimizing the gaps between the 2 cylindrical lenses and the offset lens reduces the aberrations even more. Considering these major drawbacks the feedforward calibration was a success and can only improve if the above points are dealt with.

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