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FOCUSING CRITERION IMPLEMENTATION FOR A BIOCULAR EYE SIMULATOR

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Focusing criterion implementation for a biocular eye simulator

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Abstract.

We report the design and implementation of an easy to carry out focusing algorithm for a biocular eye simulator whose eyes consist in a doublet lens (Edmund Optics 32315, F=40 mm, $f_{\#}$=3.2) nominally focused at infinity and a CMOS sensor (IDS UI-1242LE-NIR) with 5.3 μm pixel size that plays the role of the retina. The aim of the present work is to find the best focus position for each of the eyes of the biocular eye simulator when trial lenses of different power (C.I.O.M. 103/T TRAY) are positioned before them. The procedure consists in moving a slanted edge test using a linear translator and recording a set of images around the position that is perceived in focus using the naked eye. For each of the recorded images the MTF is computed using the slanted edge method. Finally, a maximum contrast criterion is applied through a selected spatial frequency in order to determine the best focus position. In order to perform the focusing evaluation an objective lens (Xenoplan 2.0/28 mm compact, F=29.3 mm, $f_{\#}$=2.0) acting as a collimator, a slanted edge and a linear translator (M-UMR5.25) were used.

Keywords: Slanted edge method, MTF, focus criteria, focus function, CMOS sensor

1. Introduction

When designing an optical system one of the main points is to diminish aberrations as much as possible. In most of the cases, focusing an optical system is one of the first operations that one should do in order to ensure that the optical system works properly. Note that the impact of defocus in the image quality is greater than the one introduced from other aberrations. Actually, is one of the first order terms from the Seidel aberration expansion [1]. In 1955, H.H. Hopkins [2] established a relation between the response of a system to spatial frequencies and its defocus from the Fourier optics point of view, namely the behaviour of the optical transfer function (OTF). At the beginning of the 70's, thank to the increase of computing power, people started to apply different types of algorithms as a focusing method. There are mainly four groups of algorithms: derivative based, statistical, histogram based and intuitive [3]. Derivative based algorithms are related to the study made by Hopkins since they are based on the assumption that focused images have more high frequency component than defocused images. Statistical algorithms use mathematical concepts as correlation and variance, they are more robust against noise than derivative based algorithms. Histogram based algorithms use histograms to analyse the distribution and frequency of image intensities, for example, one of this type considers that focused image contains more information than images out of focus. Finally, intuitive algorithms use simple assumptions to decide which image is on focus.

The diversity of algorithms found is mainly due to the need of finding the focus when working in microscopy. In optical microscopy samples are objects whose index of refraction is very close to the index of refraction of the surrounding medium (phase objects), producing images with low contrast. To solve this problem different techniques are implemented to make images sharper: differential interference contrast (DIC), dark field microscopy, phase contrast microscopy, etc. Depending on the implemented technique we obtain different kind of images and this usually determines the algorithm to be used. We have to consider that optical microscopy has recently become an important trend in science: Nobel Prizes in Chemistry on 2008 and 2014 are related with this field [4].

Even though in most cases defocus is considered an aberration in microscopy, it has been shown that if it is controlled it can be used as a technique to image [5]. Defocusing microscopy uses the information above and below the focus plane to obtain information about the surface of the problem object. When the index of refraction of the phase object is constant results are equivalent to the ones that would be obtained using phase contrast microscopy. Images that are obtained using defocus microscopy are a mapping of the object's surface while phase contrast microscopy gives information about the thickness of the object.

We report the design and implementation of an easy to carry out focusing algorithm for an optomechanical system. The optomechanical system is a biocular eye simulator whose eyes consist in a doublet lens (Edmund Optics 32315, F=40 mm, $f_{\#}=3.2$) nominally focused at infinity and a CMOS sensor (IDS UI-1242LE-NIR) with 5.3 μm pixel size that plays the role of the retina. In order to perform the focusing operation and evaluation an objective lens (Xenoplan 2.0/28 mm compact, F=29.3 mm, $f_{\#}=2.0$) acting as a collimator, a slanted edge and a linear translator (M-UMR5.25) were used. The aim of the present work is to find the best focus position for each of the eyes of the biocular eye simulator when trial lenses of different power (C.I.O.M. 103/T TRAY) are positioned before them. The procedure is related with the one used in [2] and consists in moving a slanted edge test using a linear translator and recording a set of images around the position that is perceived in focus using the naked eye. For each of the recorded images the MTF is computed using the slanted edge method [6]. Finally, a maximum contrast criterion is applied through a selected spatial frequency in order to determine the best focus position.

2. Theoretical background

2.1. Depth of field (DoF) and focus function

For any imaging system there is a plane of the object space where the sensor is able to obtain the best image. This plane is called the best focus plane (BFP). Any two-dimensional object placed at this plane will be sharply imaged onto the sensor. From the geometrical optics point of view a point at the BFP will be imaged as a point on the sensor plane. If we move this point after or before the BFP, instead of a point a disk will be imaged onto the sensor. There are two planes, one before (front plane) and other after (rear plane) the BFP where the disk is just small enough to be indistinguishable from a point i.e. the disk has the size of the circle of confusion (CoC); in digital imaging the CoC is of the order of the pixel size. Then our camera will image objects between these two planes as if they were at the BFP. The distance between the front plane and the rear plane is called depth of focus (DoF). See figure 1.

It can be shown [7] that the DoF can be expressed as a function of the parameters of the lenses and sensor working together (the camera)

$$DoF = \frac{2f^2D^2Nc}{f^4 - D^2N^2c^2}, \tag{1}$$

where f is the effective focal lens of the lens camera, D is the distance from the principle plane where the object is placed, N is the f-number ($f_{\#}$) and c is the circle of confusion.

Regardless the existence of the DoF one would like to be able to construct a spatial-dependence function in order to find the BFP. Ideally, the focus function (see figure 2(a)) has to fulfil the following criteria [8]:

- Unimodality. The focus function must have only one maximum.
- Accuracy. The maximum of the focus function must coincide with the position of the BFP.
- Reproducibility. A sharp top of the maximum imply good reproducibility.
- Range. The function must provide information about a certain range around the maximum.

Let us consider that our minimum displacement is smaller than the DoF. In this case instead of a sharp maximum we will find a flat top (see figure 2(b)) due to the sharp images obtained within the DoF. On the other hand, if our minimum displacement is bigger than the DoF we could find a sharp top but it may not coincide with the position of the BFP as is shown in figure 2(c). Besides the DoF, other factors like noise, diffraction and aberrations such as spherical or coma, deviates the focus function from the ideal one (see figure 2(d)). This fact is more noticeable when for a given object position image quality varies along the image plane, resulting an image with sharp and blurred regions.

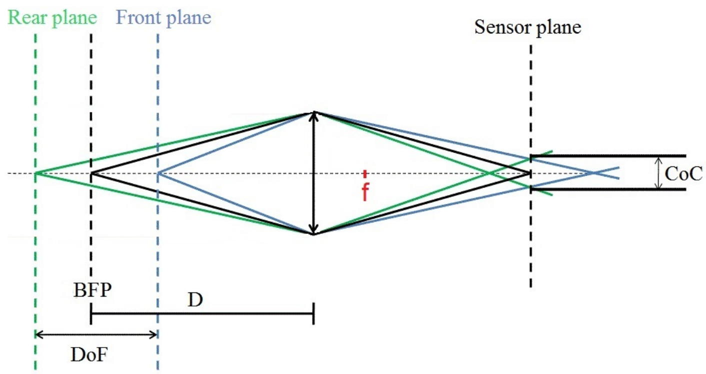


Figure 1. Schematic representation of the DoF of a single lens using ray tracing. The rays departing from the rear plane (green) and the front plane (blue) form disks that are is indistinguishable from a point due to the pixel size. The distance between this two planes defines the DoF.

All in all, it is understandable the different approaches, shown in section 1, to find the in-focus position of an optical system.

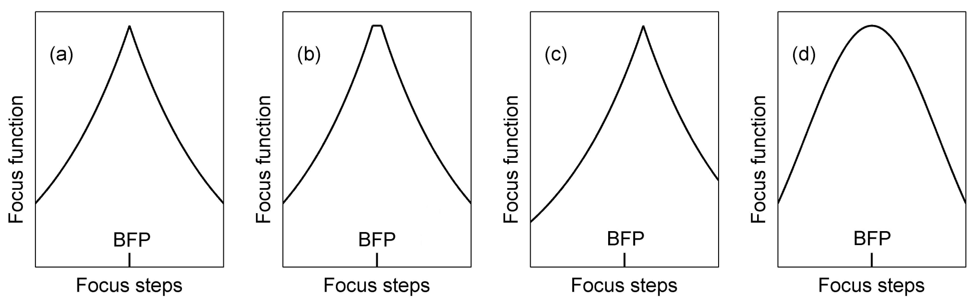


Figure 2. Illustrative representation of different focus function: (a) ideal case in which our function fulfils all the criteria, (b) the focus function has a flat top instead of a sharp one due to the DoF, (c) the sharp top of the focus function does not coincide with the real in-focus position due to the fact that the DoF is smaller than the focus step precision, (d) expected focus function when factors such as diffraction, noise and aberrations are considered.

Now we will introduce the method used in our criteria to build the focus function.

2.2. Slanted edge method: fundamentals

According to Fourier optics any two dimensional object can be decomposed as a superposition of sinusoidal functions. Taking advantage of this property one can characterize the performance of an imaging system analysing how the system images sinusoidal patterns of different frequencies. The modulation transfer function (MTF) is defined as the ratio between the Michelson contrast (also called visibility) of the image of the sinusoidal pattern and the Michelson contrast of the sinusoidal object pattern for each frequency [1]:

$$MTF(\nu) = \frac{MC_i(\nu)}{MC_o(\nu)}. \tag{2}$$

The use of the modulated transfer function (MTF) as a function of the spatial frequency is a widely extended description of the performance of any optical system. It can be applied not only to lenses but also to sensors and diffusers.

An alternative way of computing the MTF without the need of taking several images of sinusoidal patterns was proposed by the International Organization for Standardization (ISO) [9]. It is called slanted edge method (SEM) and is based on Fourier analysis. It can be shown [10] that using this method the one-dimentional MTF can be expressed as:

$$MTF(u,0) = \left| FT\left\{ \frac{\mathrm{d}}{\mathrm{d}x} ESF(x) \right\} \right|, \tag{3}$$

where ESF(x) is the edge spread function of the system.

2.3. Slanted edge method: implementation

If we want to characterize a digital biocular eye simulator using the SEM we have to consider the discrete nature of the sensor: in order to acquire an image with a smooth transition between the right-hand side and the left-hand side the edge is tilted (figure 3(a)). The inclination angle does not affect the final result [11] but and edge perpendicular to the sensor is preferably avoidable.

The first step in the implementation of the method consists in determining the inclination angle by performing the gradient to the image of the edge and then using the least square method in order to find its inclination. Secondly, using the measured angle we compute the edge spread function considering the grayscale value of each pixel and arranging them with respect to its horizontal distance from the edge (figure 3(b)). Thirdly, we compute the gradient of the ESF in order to obtain the line spread function (LSF) (figure 3(c)) and finally we perform the modulus to the Fourier transform of the LSF to obtain the MTF (figure 3(d)).

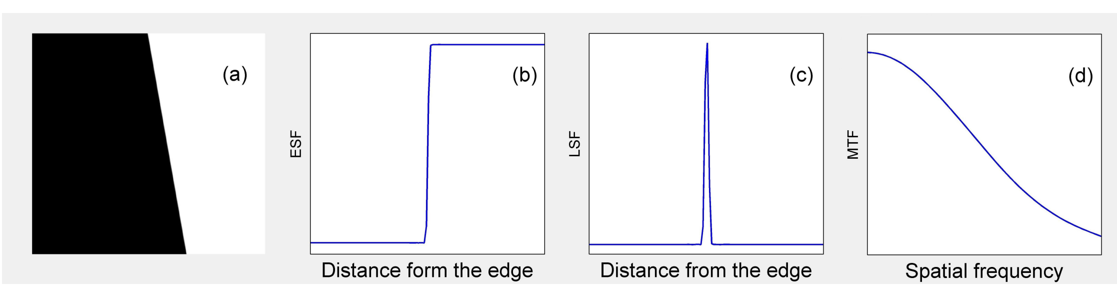


Figure 3. Representation of the SEM: (a) image of the slanted edge, (b) ESF computed from the image of the slanted edge, (c) LSF calculated from the differentiation of the ESF and (d) MTF obtained from the modulus of the Fourier transform of the LSF.

Following, we present the criterion used to construct the focus function.

2.4. Constructing the focus function

The criterion that we use is based on the assumption that defocused images have a significant loss in contrast for intermediate frequencies. We avoided to take low frequencies as a reference because for this ones near the focus the loss in contrast is too similar. Also, we declined to take high frequencies as a reference like derivative based algorithms do (see section 1), because noise has a huge impact when computing the loss in contrast for high frequencies [12].

In order to find the position of the BFP we displace the slanted edge from a region where we clearly see the edge defocused to a region where we perceive again the slanted edge defocused. During the displacement we take images from the slanted edge, we choose a region of interest (ROI) mainly to avoid vignetting and we compute the MTF for each position using the slanted edge method (sections 2.2-2.3). In figure 4(a) we show a schematic example‡ of MTFs from different positions. For these plots we look for the frequency at which the MTF decay to 50% of their value (MTF50) and we represent each frequency against the position where the image was taken (figure 4(b)). Then we choose a frequency within the range of frequencies from figure 4(b). Finally, we represent the loss in contrast for the chosen frequency against its pertinent position (see figure 4(c)). We define the position where the chosen frequency has higher contrast as the in-focus position. In the example shown in figure 4 d_3 would be defined as the position of the BFP. Note that we define, not assume, because in the last stage we need to have an unique answer to the BFP position.

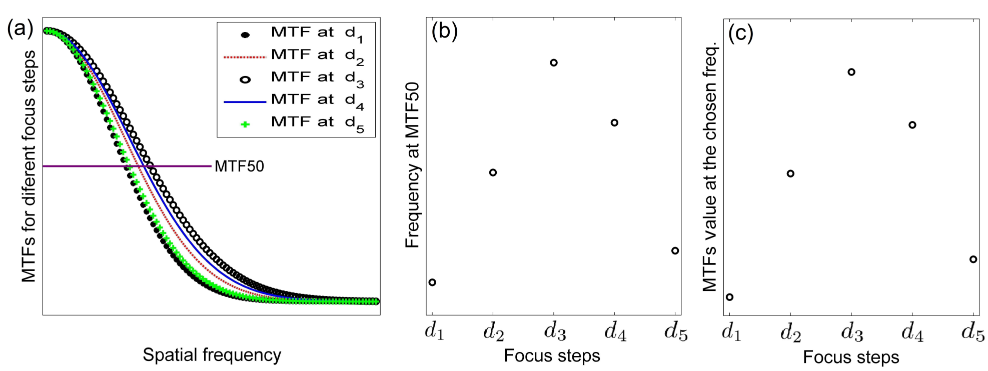


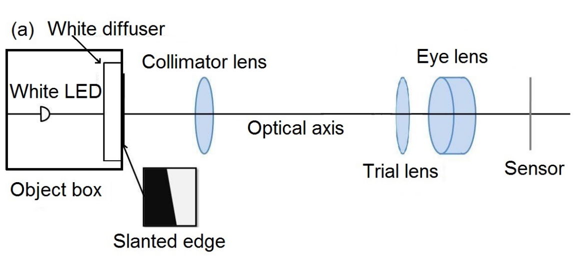
Figure 4. Criterion methodology representation: (a) MTFs computed from slanted edge images taken at different position, (b) frequencies at which the MTF decays at 50% of its value as a function of the focus step and (c) after choosing a particular spatial frequency we represent its contrast as a function of the step focus. The step focus where the contrast is higher is considered as the in focus position.

‡ For the sake of simplicity the MTF shown are Gaussian functions not real computed MTFs.

3. Experimental set-up

In order to characterize each one of the eyes of the biocular eye simulator, which in principle are focused at infinity, we used the the following experimental set-up (see Figure 5 (a) and (b)). The light source is a white LED followed by a light diffuser in order to have the object illuminated homogeneously. The slanted edge is made just putting a black cardboard attached to the white diffuser on the overture of the box. The slanted edge of 17.7×13.5 mm tilted 37° with respect to the vertical direction is located before a collimator lens (Xenoplan 2.0/28 mm compact, F=29.3 mm, $f_{\#}$=2.0) using a linear translator (M-UMR5.25) with a precision of 20 μm. This produces a sharp image that will be projected onto the sensor (IDS UI-1242LE-NIR) through the trial lens from a trial lenses set (C.I.O.M. 103/T TRAY) and the doublet lens of the corresponding eye, (Edmund Optics 32315, F=40 mm, $f_{\#}$=3.2) for both channels. In order to image the slanted edge sharply with the biocular eye simulator it is clear that its position with respect to the collimator lens depends mainly on the power of the trial lens (3D, -3D, 5D and -5D in our case) and on the fact that the sensor could not be at the nominal position. The first point is clearly under control because when performing the experiment we decide the power of the trial lens. The second point can be taken into account in the following way. We measure the position at which the slanted edge should be placed in order to be projected at infinity by the collimator lens using a calibrated focometer (Moller-Wedel AKR 200/40/14,7). Then placing the slanted edge at this position we try to image it with the biocular eye simulator, if the image is not clear, we conclude that the sensor has a deviation from the nominal position. At the end this will simply imply a shift in the position of the BFP.

In order to align the experimental set-up we designed the mechanical surface made of aluminium that can be seen in figure 5 (b). It has three different regions where the linear translator, the collimator lens and the biocular eye simulator are placed. Each region has different height in order to make the optical axis to pass through the center of the slanted edge.



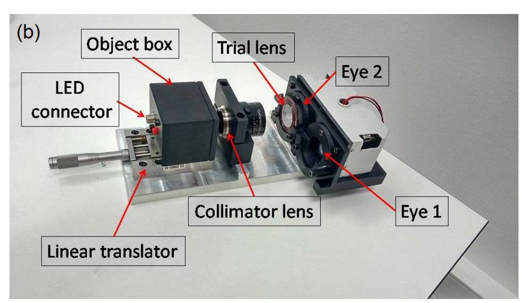


Figure 5. Image of (a) the schematic set-up considering only one of the eyes of the biocular eye simulator where we show the LED, the diffuser and the slanted edge inside a box, the collimator lens, the trial lens, the lens of the pertinent eye and the sensor; (b) the real set-up where we can see the box where in the LED and the slanted edge are located, the linear translator, the collimator lens, the trial lens and the biocular eye simulator.

The images taken to compute the MTF using the slanted edge method had a resolution of 1280×1024 pixels. When recording the images using the eye 1 we chose a unique ROI of 400×400 pixels centered always at the same point. However when recording the images using the eye 2, due to misalignment we were not able to choose a single ROI and to avoid vignetting for all the powers of the trial lenses. Hence in the case of the eye 2 we were forced to change the center of the ROI for some of the trial lenses in order to have a big enough ROI; namely, 400×400 pixels.

4. Results

The frequencies at which the MTF has the nearest value to MTF50 at several focus steps for different powers of the trial lens can be seen in figures 6(a) and 7(a). Using these curves as a reference we chose a particular frequency for each case. In figures 6(b) and 7(b) the values of the MTFs for each chosen frequency at different focus steps are shown. It should be clear that both figures 6(a) and 7(a) are illustrative because when computing the MTF we do no obtain the frequency whose MTF value is exactly MTF50. That is why in some curves for different focus steps we have the same frequency. Nevertheless to construct the focus functions that appear in figures 6(b) and 7(b) we chose a frequency whose contrast was computed in all the focus steps in order be consistent.

4.1. Eye 1 characterization

Before looking at figure 6(a) one could be tempted to assume that the performance of the system, i. e. the frequency at which the MTF reaches half of its maximum value, will decrease for increasing values of the trial lens power. The fact is that there is not a direct relation between them. As we mentioned in section 2, when constructing the focus function aberrations have an important and uncontrolled impact. Then it is not surprising that the performance of the system due to aberration compensation does not have a linear behaviour with respect to the trial lens power.

Let us consider the focus functions from figure 6(b). In all the five cases we determined the position of the BFP within an error of 1 focus step, i.e. 20 μm, as the position where the function has its maximum value. Moreover all the focus functions but the ones with the trial lens of -3D and -5D are monotonically increasing functions before the maximum and monotonically decreasing after the maximum.

4.2. Eye 2 characterization

The characterization of the eye 2 is a good example of the importance of the ROI. In figure 7(a) we see a dramatic difference between the frequencies around MTF50 with no trial lens, 3D and 5D; and -3D and -5D. This huge difference did not appear when characterizing the eye 1. In section 3 we mentioned that our slanted edge was simply constructed putting a cardboard onto the white collimator. This implies that there will be appreciable defects in the object. If one choose always the same ROI, as done for the eye 1, defects affect all the cases equally. However, if we do not choose the same ROI there will be defects in one of the ROIs that may not be present in the others. The behaviour of the curves that we observe in figure 7(a) are not only due to aberration compensation but also to the fact that we chose different ROIs. For this reason it is mandatory, as we did, to use always the same ROI for a given power of the trial lens in order to build a consistent focus function.

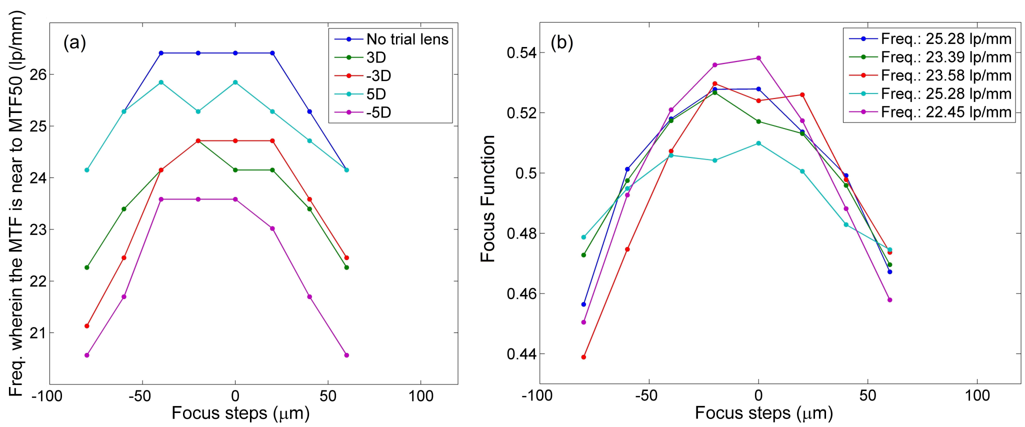


Figure 6. Building the focus functions for the eye 1: (a) frequencies around the MTF50 value for each of the powers of the trial lens at different focus steps, (b) constructed focus functions for different powers of the trial lens using the loss in contrast for a given frequency at different focus steps.

In figure 7(b) we present the focus function for the eye 2. Their behaviour is similar to the one found for the eye 1. Again we determined the position of the BFP within an error of 1 focus step and all the focus functions are monotonically increasing before the maximum and monotonically decreasing after the maximum but the one for -5D.

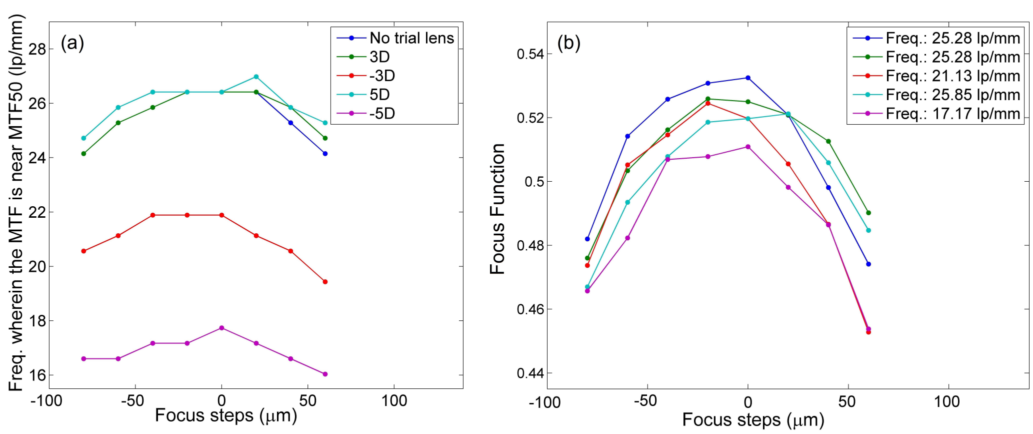


Figure 7. Building the focus functions for the eye 2: (a) frequencies around the MTF50 value at different focus steps for each of the powers of the trial lens, (b) focus functions constructed using the loss in contrast for a given frequency at different focus steps when using different trial lenses.

5. Conclusions

In conclusion, we have demonstrated the implementation of an easy to carry out focusing algorithm for a biocular eye simulator using the slanted edge method. The focus functions obtained behave well enough to determine the position of the BFP within an error of 20 μm. We have shown that focusing is the first and one of the most important steps in order to make an optomechanical system to work properly. In addition, to find the position of the BFP it is not as simple as one could expect in advance. Otherwise there would not be in the bibliography so many ways to perform this operation. This experiment could be improved implementing the slanted edge method using a more sophisticated slanted edge and comparing its results with other focus algorithms. This implementation represents a single, compact and practical approach to find the BFP of an optical system.

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