DETERMINING CALIBRATION PARAMETERS FOR A HARTMANN-SHACK WAVEFRONT SENSOR

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Abstract: Adaptive Optics has become an important technology to reduce the effect of wavefront distortions. It is used, for instance, to compensate the effects of atmospheric distortion in astronomical telescopes and to reduce the impact on the quality of the retinal image caused by optical aberrations inserted by the cornea and eye optical path. A wavefront sensor is an important part of an adaptive optical system and in the Hartmann-Shack method three parameters must be estimated prior to the wavefront estimation step: the distance between the microlens array and the image-sensor chip; and the pixel pitches in the X and Y directions in the Hartmogram image. This paper presents one method to estimate the actual distance between a microlens array and an image sensor; and another method to calculate pixel pitches, both based on image processing techniques and geometric analysis.

Keywords: microlens array, wavefront sensor, Hartmann-Shack method, adaptive optics, calibration

1. INTRODUCTION

The Hartmann-Shack method is a widely employed wavefront sensor technique to measure distortions on a light beam phase profile [1] [2]. It consists of a light sampling plane composed of a microlens array [3], replacing the objective lens, positioned at some distance from an image sensor (camera). The light beam reaching the microlens array is sampled into as many light focal points (spots) as the number of microlenses, where the location of each spot on the focal plane is proportional to the respective local tilt of the wavefront [1]. To correctly reconstruct the wavefront, three parameters must be determined: the distance D between the microlens array and the image-sensor chip [4], pitch X (horizontal) and pitch Y (vertical) in the Hartmogram image for wavefront reconstruction. The distance D affects the correspondence between spot displacements and the respective wavefront local tilt; the image-pixel pitches, if not properly assessed, might erroneously lead to the inference of astigmatism on a cylinder-free wavefront. These parameters are shown in Figure 1.
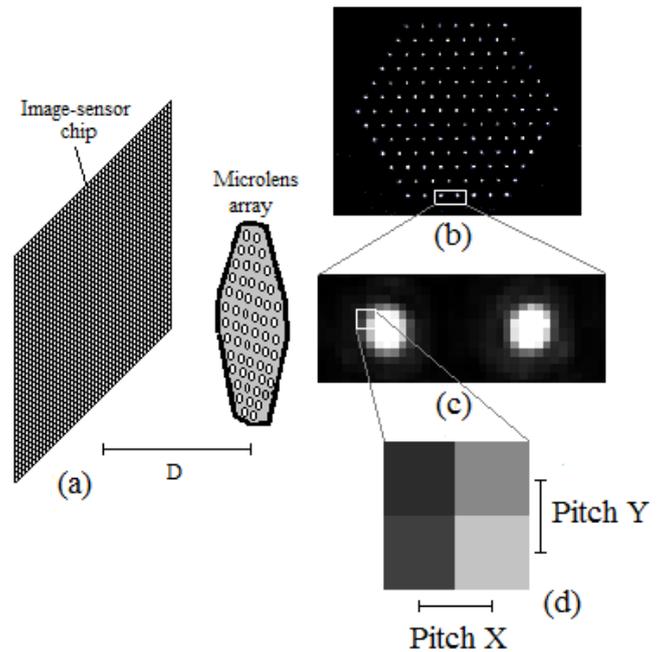

Figure 1: (a) Distance between the microlens array and the image-sensor chip. (b) Hartmogram: image of the microlens array focal plane on the computer screen. (c) Zoom of the selected region in Figure 1b. (d) Zoom of the selected region in Figure 1c displaying pixel pitch in X and Y directions.

By perpendicularly illuminating the array of microlens with a perfectly collimated light beam, the spots that reach the sensor are aligned with the optical axes of their respective microlenses. This means that there is no displacement between the spots and the microlenses optical axes. This is shown in Figure 2, where Q is the distance between adjacent microlenses centers, also called grid pitch and f its focal length.
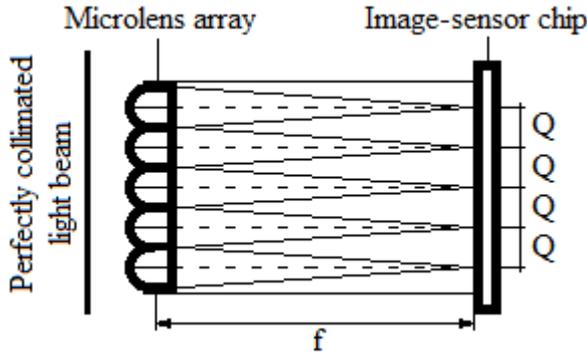
Figure 2: Microlens array illuminated with a perfectly collimated light beam.

If the beam propagates as a given spherical wave, there is some displacement between the spots and the optical axis of the microlens which is shown in Figure 3 and assigned by d.
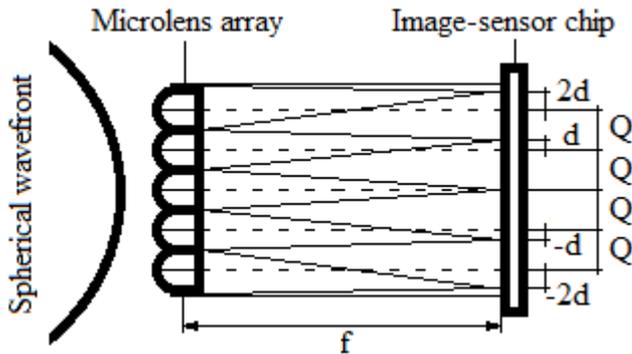

Figure 3: Microlens array illuminated with a light beam with spherical phase profile.

From Figure 3 one observes that the displacement is null for the central spot, and increases for the microlenses towards the edges, keeping proportionality to the correponding wavefront tilts. The distance between the array and the sensor is f. Geometrically, if this distance is longer than f and the sphericity of the wavefront is maintained, the displacements become larger; and if the distance is shorter, the displacements are reduced. In both cases the proportionality between the displacements of the resulting spots remains constant.

In the Hartmann-Shack method [1] [2], the wavefront reconstruction uses the displacements of the spots from their reference positions (e.g.: obtained from a plane wavefront). The distance between the centers of two adjacent pixels (pitch) in the image should be calculated to prevent the incorrect introduction of artifactual astigmatism (cylindrical component) in the wavefront estimation. In the image-sensor chip, even if the photosensitive area of the pixels is square, there might still be a difference between X and Y pitches on the image sensor due to the usual assymmetrical arrangement of metal interconnection lines and electronics on chip. On the other hand, as regards the resulting image, the pixel pitch in X an Y directions corresponds 1:1 to its width and height, respectively, as shown in Figure 1d.

Currently these parameters can be obtained as a result of a calibration procedure of a commercial wavefront-analysis software [6]. Other image processing softwares [7][8] provide toolboxes for camera calibration, but as they are not intended for wavefront sensor calibration, they do not provide the actual distance between the microlens array and the sensor.

2. OBJECTIVES

To develop an experimental method to verify the actual distance between a microlens array and a camera sensor and another method to calculate the image-pixel width and height. The accurate assessment of these parameters is essential to calibrate the sensor prior to wavefront measurement and reconstruction, contributing to the minimization of the reconstruction error.

3. RESULTS

The camera used in this experiment is a µEye UI2210-SE-M-GL with CCD (Sony) sensor technology, monochromatic, 75 fps and 640x480 (h x v) resolution. We developed an algorithm using C language and the OpenCV library to count the number of white pixels in an image captured with the camera. To count the white pixels, the image must be previously binarized since it is an 8-bit gray scale image . Moreover, the pixel digital outputs have 256 values between black and white being necessary to consider white pixels those with values above a fixed threshold. This threshold value was carefully chosen as 100 to ensure that pixels are only selected as white pixels if they are actually illuminated by light spots, resulting from their corresponding microlenses, and not otherwise colaterally hit by light coming from boundaries and/or interstitial artifacts. A hexagonal microlens array with 127 lenses, a grid pitch of 300µm and nominal focal length of 17±0.5mm was attached to a 1 inch diameter C-mount circular piece that fitted a threaded tube connected to the camera. During the experiment, the position of the array was longitudinally changed by turnning the support piece. This is shown in Figure 4.
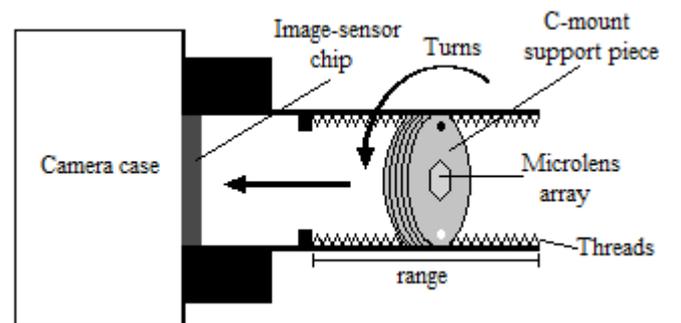

Figure 4: Schematic diagram of the experiment.

This experiment aims to position the sensor on the focal plane of the microlens array. There the intensity profile of the light spots feature their smallest lateral dimension and consequently yield the lowest number of white pixels in the image.

In practice it is difficult to make sure that the sensor is positioned at the microlenses foci because there is a mechanic enclosure (case) used to protect the camera image-sensor chip which precludes direct verification of the array

position and the use of instruments such as pachymeters and micrometers. This is the reason why the distance measurement is gauged indirectly with image processing.

The array support piece was moved progressively towards the sensor until it reached its maximum range which is 2.3mm. Four situations were considered: no, one, two and three turns in the piece, eventually reaching the proximity limit as shown in Figure 5.
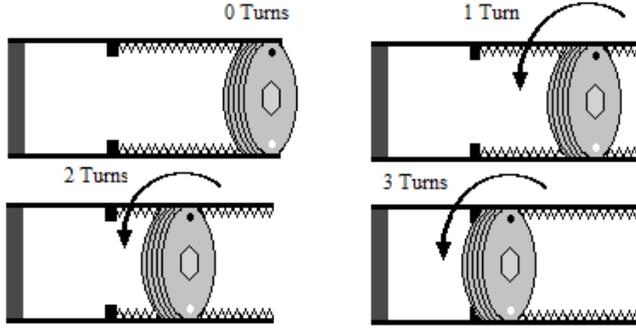

Figure 5: Schematic diagram of the experiment method.

For each array distance 300 calculations of the number of white pixels in the image were stored. The results along with their standard deviations are presented in Table 1.

Table 1: Results of the test with 0, 1, 2 and 3 turns of the microlens support piece towards the image-sensor chip.

	Number of turns	**0**	**1**	**2**	**3**
Number of white pixels	**Average**	1308.9	1245.3	1314.9	1484.8
	Standard Deviation	40.8	49.2	58.6	80.3

The equation that approximates the position of the microlens array with respect to the number of white pixels in the image was obtained from a fourth-degree polynomial approximation (Equation 1). Its graph is shown in Figure 6.

$$N_{wp} = -7.5 * T^4 + 39.8 * T^3 - 95.8 * T + 1308.9 \qquad (1)$$

Where N_{wp} is the number of white pixels in the image and T is the integer number of turns.
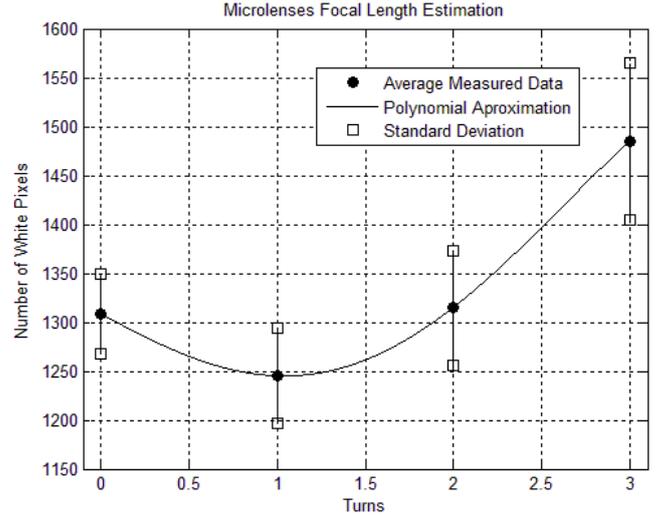

Figure 6: Number of white pixels versus the number of turns of the microlens array support.

It is known that the closer to the microlenses focus, the smaller the spots. If the spots are smaller, then the number of white pixels in the image will also be smaller. It is ideal that the array is positioned at a distance from the image-sensor chip that is equal to the microlenses foci because it is a known distance (given by its design or directly measured). In this situation, the intensity profile of each spot is closer to a circular sinc^2 profile [1] and the resulting spot image features a contour with a sharper edge. The number of turns necessary to position the array into the microlenses foci is obtained by minimizing Equation 1 and corresponds to about 1.04 turns in the piece. The angle with reference to the initial array position in the threaded tube is obtained multiplying 1.04 by 360º resulting in 374.40º ($1T$ +14.4º).

At a turn angle of 374.40º with reference to the initial array position in the threaded tube it was expected that the distance would be equal to 17$\pm$0.5mm which is the microlenses focal length used in this paper. The value of 16.88mm was then obtained with a commercial wavefront-analysis software for the distance between the microlens array and the image sensor [6]. Equation 2 shows how the percentage error of positioning is calculated:

$$Error = 1 - \frac{16.88}{17} = 0.71\% \qquad (2)$$

The distance between the microlens array and the image-sensor chip affects the reconstructed wavefront amplitude, although it does not interfere with the spatial-frequency sampling.

To avoid incorrect astigmatism introduction during wavefront reconstruction due to poor dimensioning of the image-pixel width and height a method should be developed to estimate these parameters. The relation between astigmatism and the image-pixel width variation in wavefront reconstruction is shown in Figure 7.
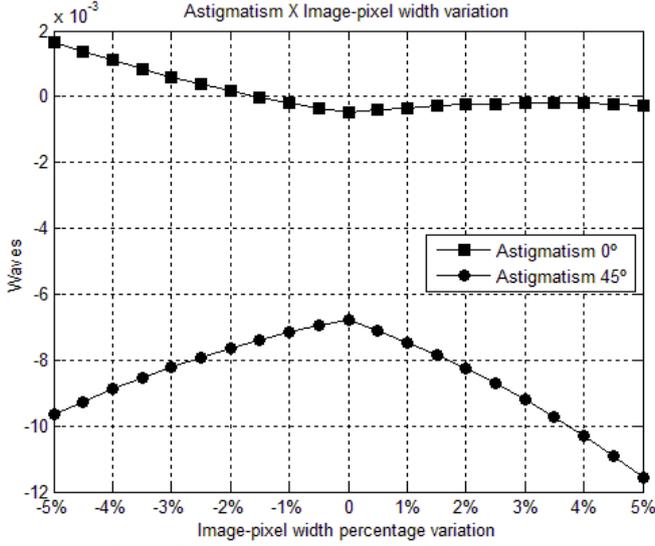
Figure 7: Relation between astigmatism introduction on wavefront reconstruction and image-pixel width percentage variation.

The astigmatism introduction error can be understood as a distortion that hampers the correct wavefront reconstruction.

This method is based on the coordinates of the spots centroids in an image of the array illuminated by a collimated light beam. A difference between the image-sensor chip pixels and the image-pixels in the computer screen is expected since the pixels in the computer have been processed, which may have changed the image resolution or its resolution depth. As the microlens array exhibits a hexagonal grid, there are columns and rows of light spots with the same X and Y pixel coordinates, respectively shown in Figure 8.
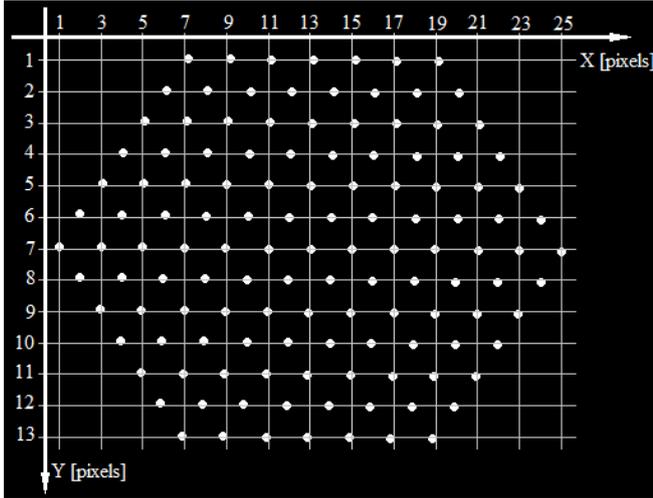

Figure 8: Rows and columns of spots that should have the same X and Y coordinates respectively.

All the spots shown in Figure 8 should in principle have the same X and Y pixel coordinates, along columns and rows, respectively. A short difference in these coordinate values is expected due to probable aberrations (distortions) on the collimating lens used in the optical setup on this experiment and/or on the microlens-array transparent glass supporting substrate.

For each row k the average $\bar{y}_k$ of the Y coordinates of the spots centroids is taken [5], according to Equation 3:

$$\bar{y}_k = \frac{1}{n_{s\_k}} \sum_{i=1}^{n_{s\_k}} y_i \qquad (3)$$

Where y_i is the Y pixel coordinate of each i spot on row k and n_{s_k} is the total number of spots on row k.

For each column j the average $\bar{x}_k$ of the X coordinates of the spots centroids is taken [5], according to Equation 4:

$$\bar{x}_j = \frac{1}{n_{s\_j}} \sum_{i=1}^{n_{s\_j}} x_i \qquad (4)$$

Where x_i is the X pixel coordinate of each i spot in the column j and n_{s_j} is the total number of spots in the column j.

The difference between the values obtained for any two adjacent rows $(\bar{y}_{k+1} - \bar{y}_k)$ is their displacement in Y direction. The average of these displacements between all adjacent rows of the array is registered as the average displacement in Y direction, according to Equation 5, where N_r is the total number of rows:

$$\bar{Y}_r = \frac{1}{N_r - 1} \sum_{k=1}^{N_r-1} (\bar{y}_{k+1} - \bar{y}_k) \qquad (5)$$

The same is valid for columns when taking the average displacement in X direction according to Equation 6, where N_c is the total number of columns:

$$\bar{X}_c = \frac{1}{N_c - 2} \sum_{j=1}^{N_c-2} (\bar{x}_{j+2} - \bar{x}_j) \qquad (6)$$

Because the microlens array is illuminated by a collimated light beam, these displacements can be related to the distance between two adjacent microlenses in the array, which is known as the grid pitch. Figure 7 shows that the distance between column 1 and column 3 is the distance between two adjacent microlens in the array. Figure 7 also shows that the distance between row 1 and row 2 is the height of the equilateral triangle the sides of which are the distance between two adjacent microlens in the array As the grid pitch of the microlens array used in this experiment is 300μm, the image-pixel width (W_{pix}) and height (H_{pix}) can be calculated in micrometers according to Equations 7 and 8 respectively.

$$W_{pix} = \frac{300}{\bar{X}_c} \qquad (7)$$

$$H_{pix} = \frac{300 * \sqrt{3}}{\bar{Y}_r * 2} \qquad (8)$$

The values obtained for the image-pixel width and height in the experiment were 9.942 µm and 9.929 µm respectively. The values of 9.899 µm and 9.909 µm were obtained, respectively, with a commercial wavefront-analysis software [6].

4.   CONCLUSIONS

To estimate the best distance between the microlens array and the image-sensor chip which is the microlens-array focus, we used the density of white pixels in the binarized image. The number of white pixels in the image reached a minimum when the array was at a distance from the sensor equal to the microlenses focal length.

The experimental distance measurement presented in this work shows 0.71% error in comparison to the value obtained by a commercial wavefront-analysis software [6]. This error can be attributed to lack of micrometric precision in the piece that supports the array and respective thread, but lies within the microlens accuracy limited by the fabrication process and material specifications. Nevertheless the results were consistent and the method can be easily implemented.

By estimating the distance between the microlens array and the image-sensor chip, the camera is capable of reconstructing wavefronts with minimized error between spot displacements and the respective wavefront local tilt.

The estimation of the image-pixel width and height consist in illuminating the microlens array with a collimated light beam while storing each spot center coordinate that must be aligned to the microlenses optical axis. These coordinates can be related to the grid pitch, which is the distance between the centers of two adjacent microlenses. The experimental pixel dimensions calculation in this work shows 0.43% and 0.20% error for width and height respectively, in comparison to the value obtained by a commercial wavefront-analysis software [6]. This error is attributed to probable aberrations on the collimating lens because the procedure used in the commercial wavefront-analysis software [6] does not include it, but is less straightforward to implement. By correctly estimating image-pixel width and height, incorrect astigmatism introduction in wavefront reconstruction is minimized.

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