High precision alignment technique through quality image analysis

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ABSTRACT

The proper alignment of the individual elements is a crucial point in the final performance of an optical system. The alignment technique we present uses the image formation of a point sources array to detect the misalignments of an imaging system. We have displaced the analysis plane from the exit pupil plane to the image plane, where the PSFs functions are captured on a sensor. The PSFs are large enough to be sensitive to the misalignments and we are able to detect them using image analysis techniques. The proposed technique is a solution when more than one field position is necessary to obtain a well-balanced quality function over all the field of view. We have been studying this method on a particular collection of optical systems with decentering and rotation errors, achieving an accuracy of 0.1mm for decentering and 0.01º for rotation.

Keywords: Alignment, PSF, image quality, adjustment process.

1. INTRODUCTION

Optical systems are designed considering certain tolerances on materials characteristics, surfaces geometry, distances and positions of the elements[1]. For imaging systems, as higher must be the quality of the image, greater has to be the precision on the elements characteristics and positions.

Although it is important to have a guarantee of the proper geometry and optical characteristics of the elements, to achieve the maximum quality of an optical system it is also important to verify the position of the elements and correct the misalignments done during the assembly. Hence, it is crucial to have a high precision alignment technique to achieve the expected performance of a high quality imaging optical system.

The bulk work of positioning during the assembly of an optical system is carried out by the mechanical mounts, which are also limited by their own tolerances. Although tolerances on mechanical positioning can be good enough to guarantee distances among elements, they can lack of effectivity in special cases. For example, if the system has a cylindrical lens, it could be especially difficult to align the cylinder axis. This is why an external system to verify the alignment of the elements is necessary when a high precision system is assembled.

There are many metrological techniques to qualify and quantify the performance and the quality of an optical system[2]. Interferometric and deflectometric techniques, such as interferometers with lateral shearing or Shack-Hartmann devices, are commonly used to test the performance of an optical system. However, if we are testing the alignment of a system, they do not provide information about which element is causing the possible quality loss.

There are few techniques to test the proper alignment of a system which provide the essential information to correct the misalignments. The technique developed by H. H. Hopkins and H. J. Tiziani [3] detects and quantifies the misalignments in order to correct them using the reflection of an image on the elements surfaces to do the measurement.

There are several commercial alignment systems based on this technique [4,5]. However, they need a high precision rotary system and thermal stabilization to assure the reference.

We present a new method to detect and quantify the misalignments of an imaging optical system based on the analysis of the image quality. We have developed a new self referenced technique where we analyze the PSF of nine point sources placed to cover the principal field positions.

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A set of simulations has been made in order to study the capability of the method to detect misalignments. It has been first applied to a simple system formed by two achromatic doublets, being sensitive to decenterings of 0.1mm. Later, it has been applied to a more complex system with non-rotationally symmetric elements, being sensitive to rotations of cylinders of 0.01º.

In this communication, we will first explain the basic concepts of the method, describing how it works. Secondly, we will present some of the results of the simulations we have done to verify the method. And finally, we will discuss the results on the conclusions and the forthcoming work we have planned to do.

2. THE METHOD

We needed a technique to detect the misalignments of an optical system, and we wanted it to be self referenced to overcome the mechanical difficulties of high precision movements, positioning and stabilization that would made it bound to be too expensive. The main metrological techniques were studied searching a solution to our problem without success, so then we decided to develop a new technique.

First of all, it was decided to change the plane of analysis from the pupil plane (usual in the conventional metrological techniques) to the focal plane, and base the analysis on the image quality instead of analyzing the wavefront.

We studied the use of a source such that covers completely the entrance pupil of the optical system under alignment, so we can analyze simultaneously axis and field positions. So an array of nine point sources distributed on the field was used as the object of the system

The choice of a source that allows the simultaneous analysis of field and axis positions has been made to achieve the maximum precision and to obtain a well-balanced quality function over all the field of view once the detected misalignments are corrected.

This source is formed by an array of nine point sources that are collimated by a well corrected objective before reaching the system under test. The nine sources should be distributed to cover the area of the sensor when forming the image. In Figure 2.1-1 there is an approximate sketch showing the distribution of the sources and the reference number we will use from now on to refer to each one of them.

This array of sources is intended to be used for a general case, but in simpler cases it could be enough with less than nine sources to do the measurement. For example, as we will see in the next section, for a simple system may be enough with sources 1,3,4,5 and 7.

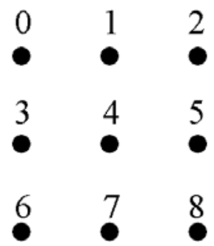


Fig. 2.1-1. Figure showing an approximate distribution of the sources on the object plane. Reference number for each source is indicated.

To capture the image of the sources on the object plane there must be an objective attached to a sensor that forms the image of the sources once the light has gone through the optical system on test. From the nine point sources of the object, we will have an image on the sensor of nine PSFs.

The designed system to do the measurements is sketched in Figure 2.1-2. It is, summarizing, formed by the nine sources, a collimator, the system under test and an objective that forms the image on a sensor.

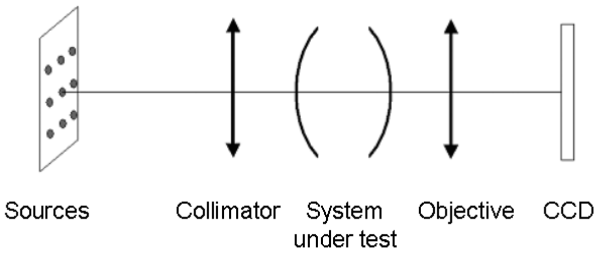


Fig. 2.1-2. Figure showing the outlines of the system. It is formed by the nine sources, the collimator, the system under test, the objective and the sensor.

The method we present is based in the image analysis; it compares the nine PSFs of an image captured by the system of Figure 2.1-2 by pairs. To do this comparison we have set a collection of calculations with the PSFs that, by means of the comparison of the shape and the relative position among them, give enough information to detect the misalignments.

First of all, we have defined two reference systems: a global one centered on the first pixel of the image, and a local one, centered in the center of mass of the PSF we are using for a specific calculation. These will be the only references used in the analysis method, becoming it self-referenced.

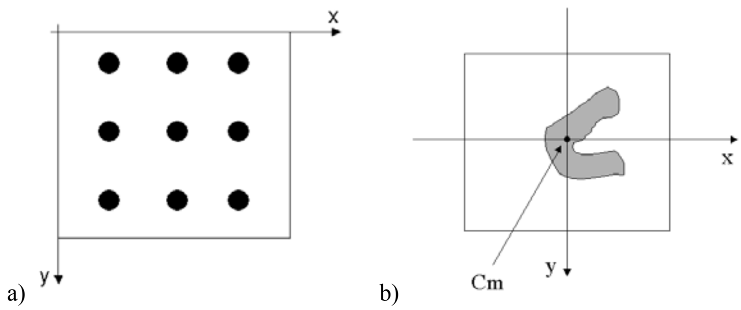


Fig. 2.1-3. Figure showing the definition of the a) general reference coordinates system, and b) local axis centred on the center of mass of a PSF.

We have seen that there are patterned differences among the PSFs for the misalignments. So an algorithm able to detect and identify these differences can give the information of which element is misaligned and how.

We have developed a first algorithm that by today is able to detect rotation misalignments. It can be seen an outline of this algorithm in Figure 2.1-4. It detects the asymmetries between pairs of PSFs and relative positions and infers which lens is misaligned.

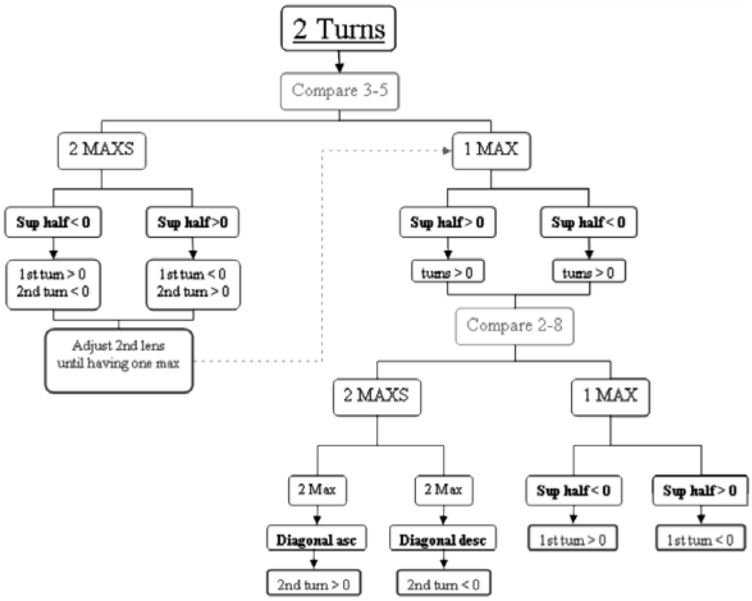


Fig. 2.1-4: Diagram summarizing the outlines of a first developed algorithm.

3. RESULTS

We have applied the presented method to two different systems. The first one is a simple system formed by two achromatic doublets where one of them is decentred. The second one is a more complex system with non-rotationally symmetrical elements where we applied different angles of rotation to them. We present the results obtained in these two studies.

3.1 Study with two doublets

As we have mentioned above, we used an array of point sources. Being a simple system, for this first set of simulations we used five monochromatic point sources: 1,3,4,5 and 7 (see Figure 2.1-1) of 4µm Ø. The system in test was chosen to be two achromatic doublets with N=4 and EFL=100mm. We first simulated the centred system, and afterwards we decentred one of the doublets 0.5mm. For each case we analyzed the position and the shape of the PSFs comparing them in pairs.

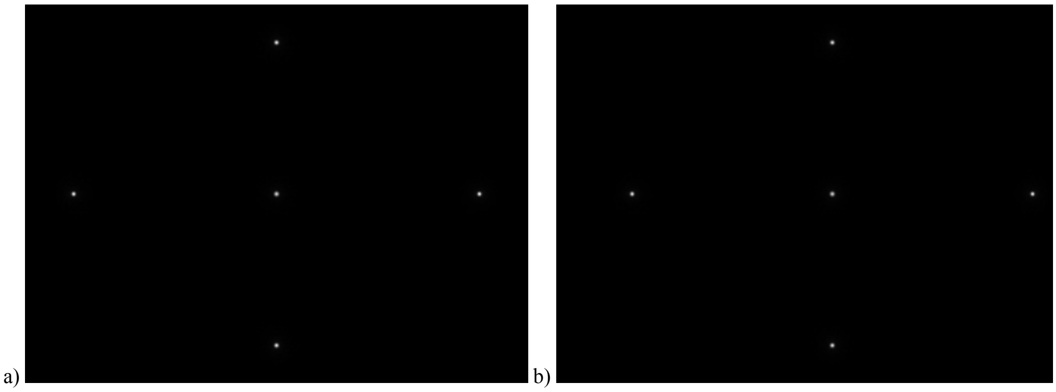


Fig. 3.1-1. Figure showing the image of the five point sources used in this first simulation when a) no decentering is applied to the system, b) a decentering of 0.5mm is applied to the first doublet. The central source is intended to be used to analyze the on axis PSF and the other four to analyze the field PSFs.

If we compare PSFs corresponding to sources 3 and 5, they are symmetric respect the vertical axis (parallel to the general Y axis, see Figure 2.1-3) that goes through the central PSF (number 4). But they lose their symmetry when we displace the first doublet. We can take, for the image of the decentred case, a profile of both PSF as indicated in Figure 3.1-2. If we rotate the profile of PSF 5 respect to his local Z axis and superimpose it with the profile of PSF 3, we get the graphic of Figure 3.1-3.

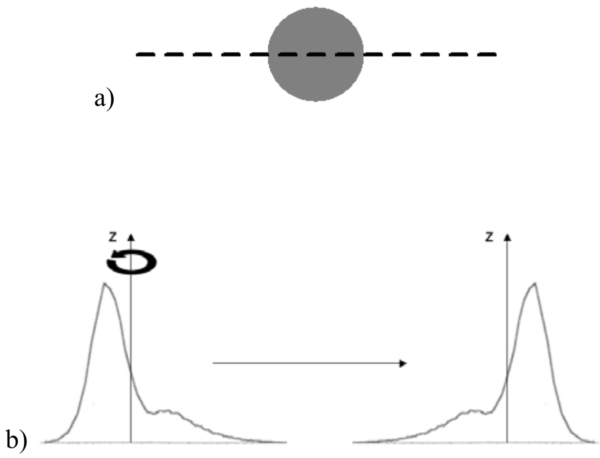


Fig. 3.1-2. Figure showing how the profile is taken. a) A sketch of how the line to take the profile is selected. b) The turn arount the local Z axis of the PSF profile.

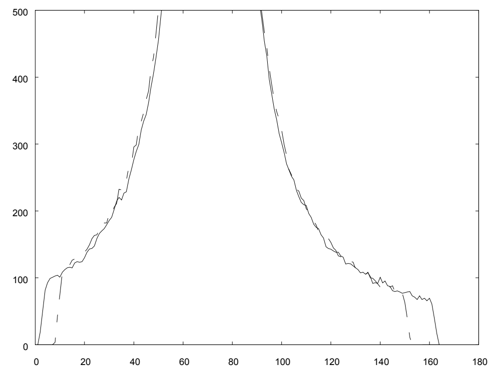


Fig. 3.1-3. Figure showing the superimposed profiles of PSF 5 (dashed line) and PSF 3 (solid line) when the first doublet is displaced 0.5mm. PSF 5 profile has been turned respect his local Z axis (as shown in Figure 3.1-2) to facilitate the comparison. On the horizontal axis is represented the distance in pixels and on the vertical axis the number of counts got on the sensor during the simulation. The vertical axis of the graphic has been cut to see in detail the difference between the two profiles.

We can see that profiles do not match, they are different due to the decentering, so the method is sensitive to the decentering of a lens of 0.5mm.

The simulation was done also for a displacement of 0.1mm. Again we compared PSFs 3 and 5 obtained in this case using the same operation. We saw, as expected, that now the difference is much smaller (see figure 3.1-4a); therefore we decided to displace the analysis plane from the focal plane to the plane where we get the circle of minimum confusion. In this new plane we obtained an image with a different set of PSFs. We compared again the profiles of PSFs 3 and 5 getting a greater difference than in the focal plane (see figure 3.1-4b), so we see that it is possible to increase the sensitivity of the method selecting properly the analysis plane to use.

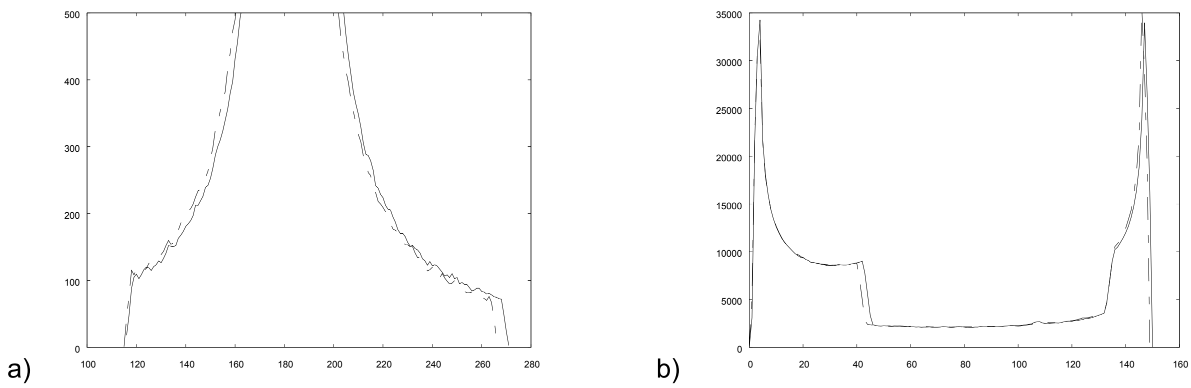


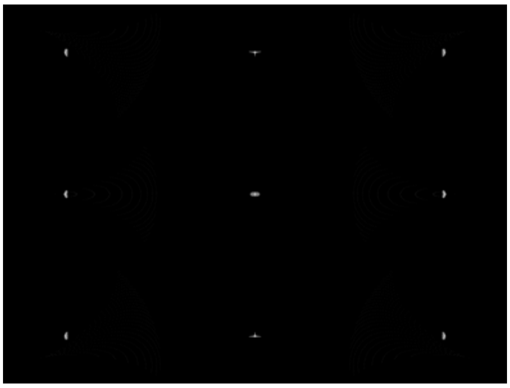
Fig. 3.1-4. Figure showing: a) the superimposed profiles of PSFs 3 and 5 when the first doublet is displaced 0.1mm. The vertical axis has been cut to see in detail the difference between the two profiles. b) The superimposed profiles PSFs 3 and 5 obtained in the circle of minimum confusion plane when the first doublet is displaced 0.1mm. The PSF 5 profile has been turned respect his local Z axis to facilitate the comparison on both cases. On the horizontal axis is represented the distance in pixels and on the vertical axis the number of counts on the sensor during the simulation.

From these results it can be expected to detect misalignments in any optical system with this method because a decentering will cause changes in field PSFs. The decentering of an element will always cause a non-symmetrical change on the system, thus field pairs as 3-5 will always have differences.

3.2 Study with a non-rotationally symmetrical system

We have done a set of simulations with a non-rotationally symmetrical system formed by spherical and cylindrical elements. Different angles of rotation around the optical axis have been applied to two of the cylindrical elements, simulating the obtained image with the designed system of Figure 2.1-2. We present here some of the results we obtained.

In figure 3.2-1a we show the obtained image of the PSFs for the well aligned system. To bring out the shape of PSFs we have cut a small squared cell around each PSF and put them together in logarithmic scale as shown in figure 3.2-1b. We can then see at first glance (see Figure 3.2-2) that there is a high symmetry among the spots if we compare them in pairs such as 0-2, 1-7, 3-5 or 6-8 (see Figure 2.1-1 for the numbering references).

a) 

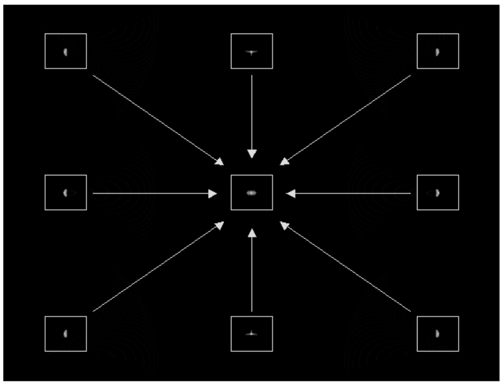
b) 

Fig 3.2-1: a) Image obtained in the simulation for a well aligned system in logarithmic scale. b) Diagram that shows how we have cut the image in nine parts and brought them together to help in the visual analysis.

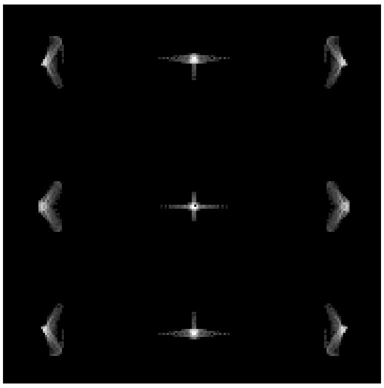


Fig 3.2-2: a) Image obtained when the cells are put together in order to do the visual analysis for the simulation for a well aligned system in logarithmic scale.

We made the simulation of the designed system with the non-rotationally symmetrical system in test for 20 different combinations of rotations of two of the cylindrical lenses; we can see some examples of the obtained images on Figure 3.2-3. In these examples we can see that there is a noticeable loss of symmetry. Now PSFs change in shape and position, rotating their maximums around the centre of the image.

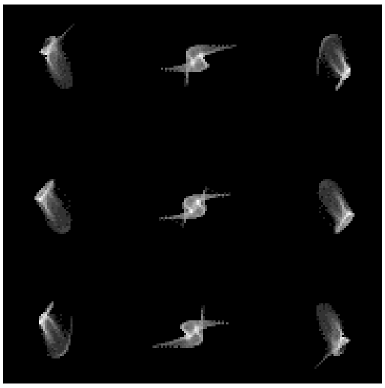
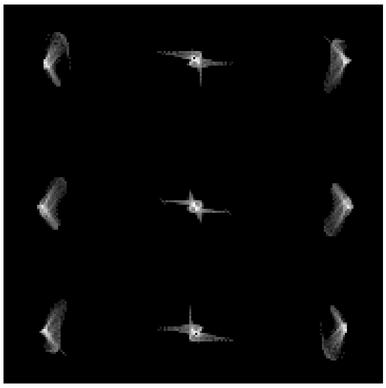
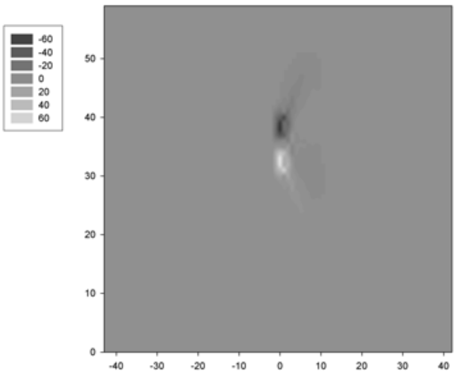
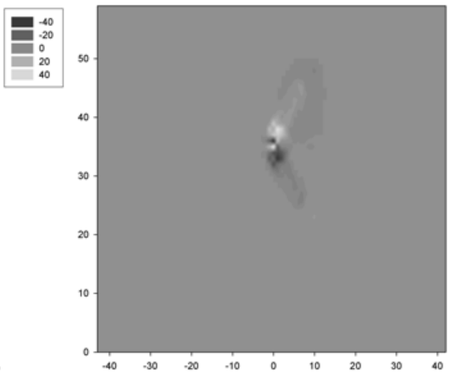
a)  b) 

Fig 3.2-3: Cut image in logarithmic scale of the nine PSFs obtained in the simulation with the non-rotationally symmetrical system with a misalignment of rotation for: a) only one cylindrical lens rotated 0.1º, b) both cylindrical lenses rotated 0.05º but in opposed ways.

We have analyzed, for each image, the differences in shape and position of the PSFs. For example, we have compared the shape and position of PSFs 3 and 5 (see figure 2.1-1 to see the numeration) by turning the PSF 5 around its local Y-axis, matching the maximums of PSFs 3 and 5, and subtracting the 5 from the 3. The result for this calculation can be seen in figure 3.2-4.



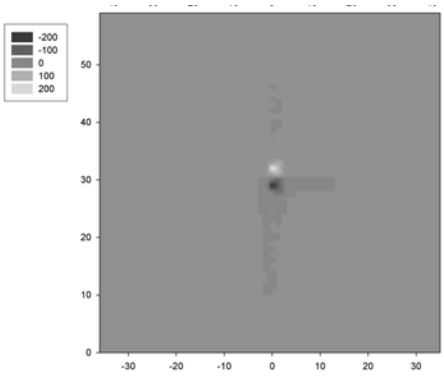
a)



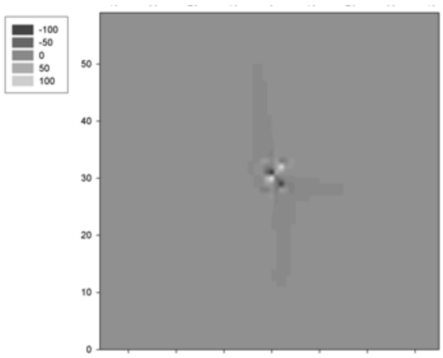
b)

Fig. 3.2-4: Graphics showing the difference between PSFs 3 and 5 when: a) a cylindrical lens is rotated 0.1º, b) two cylindrical lenses are rotated 0.05º in different way. Both graphics are in pixels in vertical and horizontal axis, and number of counts on the sensor for the grey scale.

There are high noticeable differences between PSFs 3 and 5 for all the cases of rotation we have studied. And as for this pair of PSFs, there are also noticeable differences for all pairs we can make of the 9 PSFs for each case. In figure 3.2-5 we show the difference between PSFs 1 and 7. Again, there is a noticeable difference between them.



a)

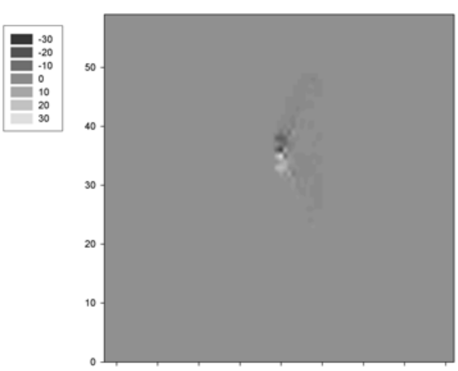


b)

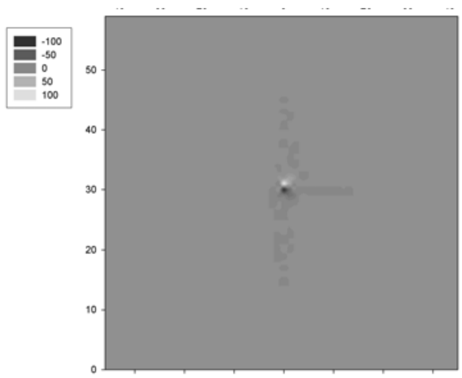
Fig. 3.2-5: Graphics showing the difference between PSFs 2 and 8 when: a) a cylindrical lens is rotated 0.1º, b) two cylindrical lenses are rotated 0.05º in different way. Both graphics are in pixels in vertical and horizontal axis, and number of counts on the sensor for the grey scale.

Therefore, comparing pairs of PSFs of an image captured with the designed system, we can detect if there is a misalignment of rotation in the system in test. Notice that this is being done without the needing of a high precision positioning system nor stabilisation device, for this is a simple self referenced method.

We have made simulations for different angles of rotation, being the smallest angle of 0.01º and the biggest of 0.1º. In figure 3.2-6 we can see the same calculus as in figures 3.2-4 and 3.2-5 but for a rotation of 0.01º on the first cylindrical lens. Although smaller, it is also noticeable the difference between the two pairs of PSFs, so with this method we can detect rotations of almost less than 0.01º.



a)



b)

Fig. 3.2-6: Graphic showing a) the difference between PSFs 3 and 5, b) the difference between PSFs 1 and 7, when a cylindrical lens is rotated 0.01º. The graphic is in pixel units in vertical and horizontal axis, and number of counts on the sensor for the grey scale units.

So we have seen in these results that, using this method, we can detect differences between PSFs that should be equal and hence detect the existence of a misalignment. In these results we can also see that by this method we are able to detect decenterings of 0.1mm and rotations of 0.01º.

4. CONCLUSIONS

We have set the basis for the design of a system capable of detecting and quantifying the alignment errors of an imaging optical system done during the assembly of it. A new metrological method has been developed, based on the image analysis by comparing field and axis position PSFs. It is self referenced and uses the image of an array of nine point sources to make the measurement, analyzing simultaneously the on axis and field positions to obtain a well-balanced quality function over all the field of view. A first algorithm has been developed to make the analysis, based on the comparison of shape and relative position by pairs of the nine field and axis PSFs.

We have applied this method to two optical systems, one simple optical system formed by two doublets and a general system with non-rotationally symmetric elements, being able to detect decenterings of 0.1mm and rotations of 0.01º around the optical axis. These results, combined with a good selection of the analysis plane, point at the successful development of a high precision alignment system.

Having now set the basis to detect the most critical misalignments, decentering and rotation, we would like to be able of, first, quantifying these misalignments, and, second, carry on the study and the development of a generalized algorithm to distinguish and quantify different kind of misalignments. This is the final objective of the method. We have done a first step in the development, but the basis is set and the first obtained results are encouraging.

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