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Simulation and development of a prototype for high precision surface metrology

Sílvia Costa[1], Manuel Abreu[1,2]

[1] Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Portugal
[2] Instituto de Astrofísica e Ciências do Espaço, Universidade de Lisboa, Portugal

Email: fc51745@alunos.fc.ul.pt

Abstract. Optical techniques are used in many applications in the metrology field, namely for high accuracy surface profiling. Although there many techniques are available, a specific measurement methodology must be correctly chosen according to the specifications of the range of measurement, field, and surface characteristics. In this work we simulate and develop a small prototype capable of measuring surfaces of circa 10 by 10 cm with an uncertainty of 20 μm in all directions, using the astigmatic method as baseline. The aim of this paper is then to show a dedicated and optimized optical setup that allow the surface characterization of a sample surface.

1. Introduction

In this work we present the development and characterization of prototype that uses the astigmatic method for surface profilometry. This technique estimates a focus error signal (FES) that represents the object's surface height variation, based on the shape and orientation of the spot produced from the astigmatic image forming optics. This method is classically choose for autofocusing and autotracking tools, widely utilized to measure film thickness – because being a noncontact-based method brings many advantages – and also for surface profiling. By choosing the astigmatic method we prevent the multiple reflections problems that can occurred in conventional interferometry.

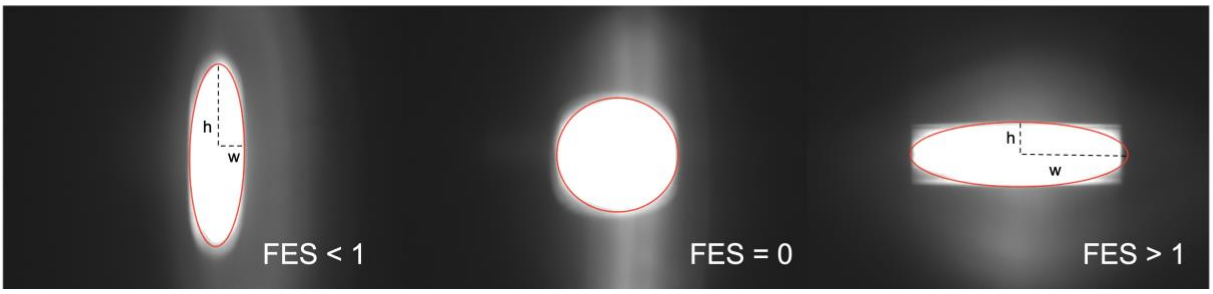

Figure 1: Variation of image according to its distance to the astigmatic lens. From left to right: the image at the tangential focal length; the image when both planes are equally focused; the image at the sagittal focal length.

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2. Analysis of the system

An astigmatic lens, contrary to a cylindrical lens, has two different focal points each one for its principal planes, tangential and sagittal. In an image forming optical system, having a point source as the object, when the tangential plane is on focus the resulting image is a vertical ellipse that changes into a horizontal ellipse when the sagittal plane is on focus, as can be seen in Figure 1.

When both focal lengths are known, we can acquire images within the specified working range and by analysing the shape of the resulting spot we can calculate the exact distance from the lens.

Basically, we are calculating the amount of defocus of the image to know its location, which is designated as the astigmatic method. The amount of defocus is calculated by the simple equation 1 that represents the Focus error signal (FES). The calculations that led us to this equation can be consulted on reference [1].

$$FES = \frac{4}{\pi}\tan^{-1}\left(\frac{w}{h}\right) - 1 \qquad (1)$$

This equation is dimensionless, and its value can vary from -1 to 1, corresponding to the focus points of the tangential and sagittal planes, respectively. When both planes are equally focused, the result is zero and we shall consider that as our reference point, meaning the system shall be calibrated for this position.

The profilometry of a sample can be made by calculating the FES for each coordinate.
The scheme of the system that was implemented is shown in Figure 2.

For the astigmatic group we chose to use two lenses, one spherical and one cylindrical, because we could change the optical power on each axis more easily, and so adapt the group lens if necessary.

2.1. Simulations and Software

The optical design was simulated in Zemax in order to maximize the measurement performance for a surface height variation range in the order of 1 mm, with a resolution better than 20 micron.
These simulations were made for several combinations of lenses that can be seen on Table 1. We chose the lenses based on their working range. The astigmatic group was designed as two lenses, one spherical and the other cylindrical, in contact without any space between them, such as in the prototype.
The microscope objective was set as a paraxial perfect lens with focal distance of 3.2 mm. The focal distance was calculated using the equation,

$$f = \frac{160}{M} \qquad (2)$$

where f is the focal distance and M the magnification of the microscope lens.

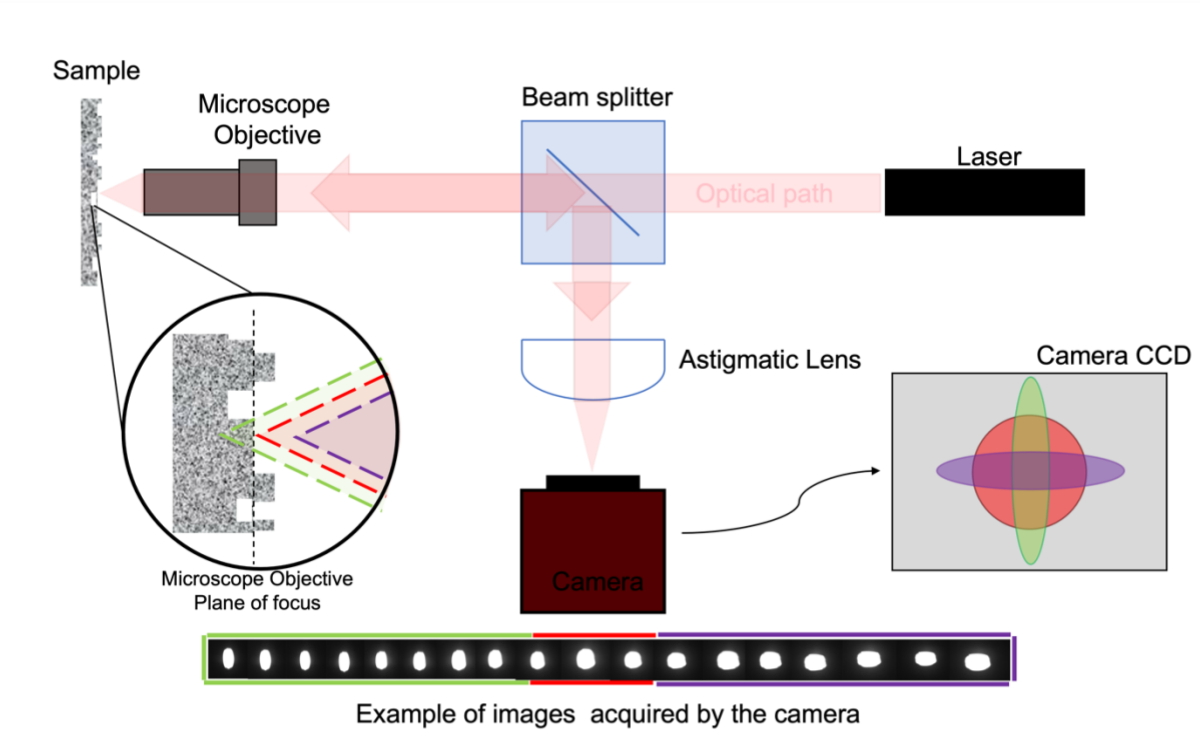
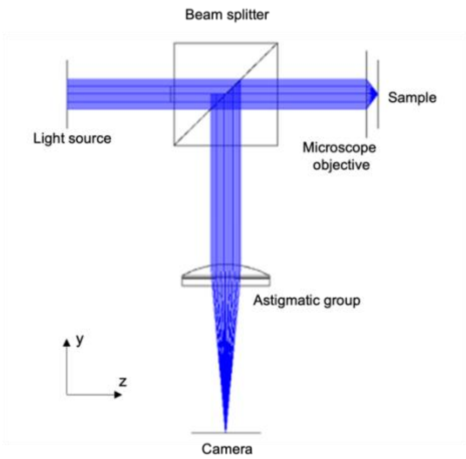


Figure 2: Schematic of the system to be implemented. When the light hits the sample's surface on a point that is not on the plane of focus, the spot on the camera CCD changes. This change of spots shape is due to the effect of the astigmatic lens.

The distances between the optical elements can be consulted on Table 2. Since the light source is collimated, the beam waist remains the same from the light source to the microscope objective. Then as the latter is an apo-planatic objective, meaning that the light reflected on the sample that travels back has the focus point at infinity, its beam waist also remains unchanged until it meets the astigmatic group.

This means that, except from the distance between the microscope objective and sample – that we assume to be at focus – the only distance that matters and influence the system is the one between the astigmatic group and the camera. Although using different distances between the optic objects on the system on Zemax configuration and on geometric optics, we came to the same result regarding the distance from astigmatic group to the camera, as can be seen on Table 2. On geometric optics we arrived at this result experimentally, by setting the astigmatic group at the distance where the image on the ccd was as the spot of the center of figure 1.

The image produced by the astigmatic optics was acquired by a high resolution camera controlled via a Labview interface. Image processing algorithms, made on Matlab, were embedded in the Labview camera controller, providing FES estimates in real time.
The software user interface can be seen in Figure 4 and it's optimized for the prototype here developed. However, the user can adapt the camera property values as needed, choosing how many images to take and where to save them. The properties available to be changed are the camera gain, exposure, and brightness.



Figures 3: System simulated on Zemax.

Working range between the focus of the sagittal and tangential planes (mm)		Focal distance of spherical lens (mm)		
		30	50	70
Focal distance of Plano cylindrical lens (m)	1	0.87	2.39	4.58
	5	0.18	0.49	0.96
	10	0.09	0.25	0.48

Table 1: Working range between the focus of the sagittal and tangential planes. The interest value that led to the chosen lenses is highlighted.

Parameters of the astigmatic optic system Distance between:	Geometric Optics (mm)	ZEMAX settings (mm)
• The light source – beam splitter (BS)	60	60
• The BS - objective	15	30
• The objective – astigmatic group	27	70
• The astigmatic group - camera	45	44.262

Table 2: Parameters of the astigmatic optic system.

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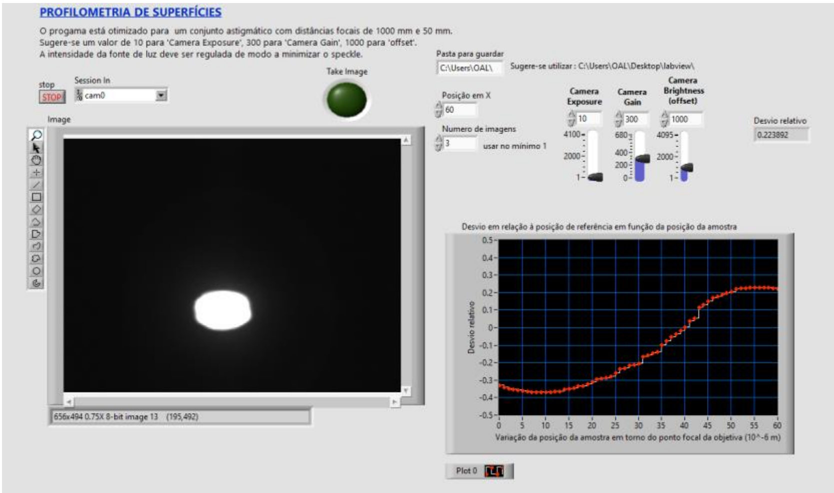

Figure 4: Software developed on LabView.

2.2. The prototype

The astigmatic group consist of a pair of lenses, a spherical and a cylindrical, with focal lengths of 50 mm and 1000 mm, respectively. These lenses were chosen based on their range of work. The lenses were mounted on the same lens mount (a C-Mount lens mount) with virtually any space between them. The objective lens is an apo-planatic microscope objective with a working distance of 10 mm and magnification of 50. The camera is a Guppy F-033 from Allied Vision.
The system is mounted in an optical breadboard, using as light source a LED with wavelength of 660 nm, collimated by an off-axis parabolic mirror. A small diaphragm was introduced between the collimator and the beam splitter to control the beam width and avoid some diffused light present in the optical path.
The manual translation stage here chosen is a linear stage of 1 axis with a travel distance of 2mm, resolution of 10 micron and uncertainty of 5 micron.

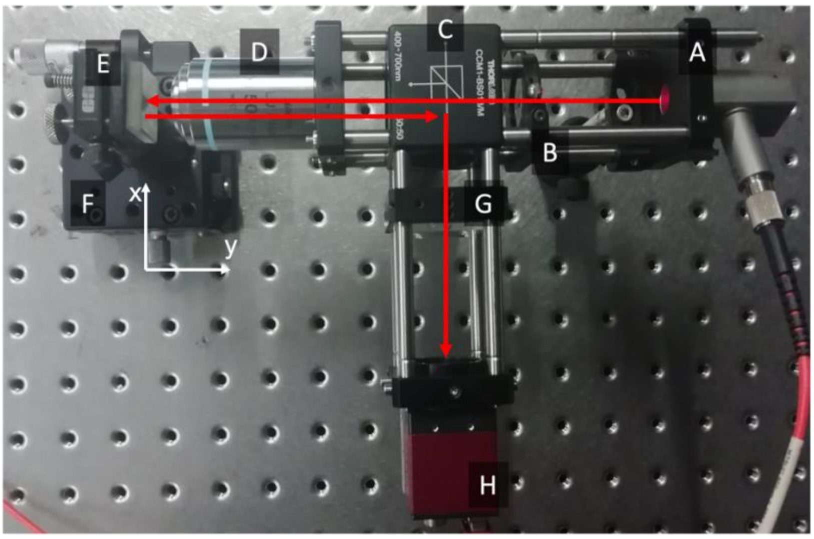

Figure 5: The prototype. It follows the same structure as planned on its schematics. A: Collimated LED; B: Diaphragm; C: Beam splitter; D :Microscope Objective; E: Sample; F: Translation table; G: Astigmatic group; H: Camera.

2.3. First experimental results

It is important to study how the measurement range changes for different types of materials, so we tested our system and estimated the FES for different object distances, for 4 different materials: a mirror, a bright metal, a dark metal, and a black plastic. The object sample was mounted on a translation stage, allowing the variation of the position of the object surface with respect to the objective focal plane within a range of 2 millimetres, with position resolution of 5 micron.

The intensity of the light source was adjusted to each sample to minimize the saturation.
The results can be seen in Figure 6 and on Table 3.

Analysing we see that the dark objects have a lower performance when compared with the bright ones. The position discrimination and range for each object was much larger for the formers, as it shows on Table 3. The process was repeated 5 times for each object.

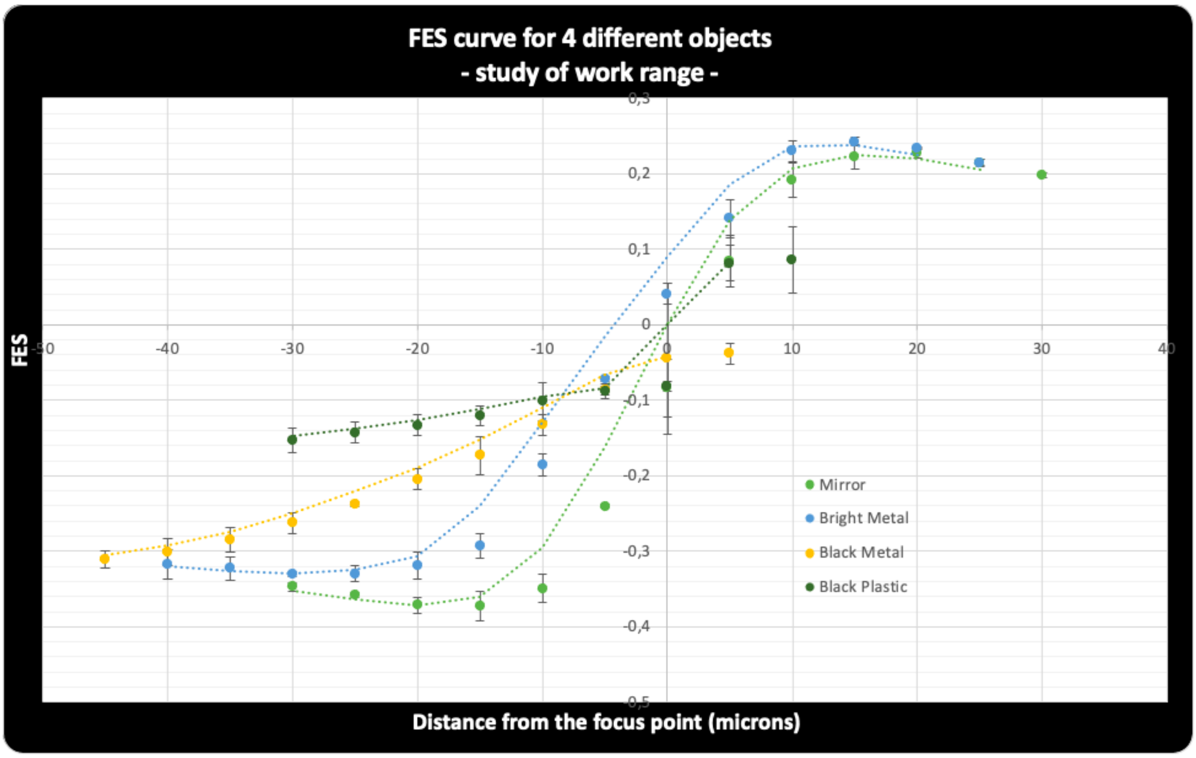

Figure 6: Graphic obtained with the experimental results for simulated FES of each sample. Note that the negative and positive values correspond to positions away and towards the focus, respectively.

Data from 4 different objects - work range of 40 micron -				
FES	Mirror	Bright Metal	Black Metal	Black Plastic
max value	0.23	0.25	-0.07	0.11
min value	-0.37	-0.33	-0.32	-0.15
max variation	0.60	0.57	0.25	0.27

Table 3: Data obtained with the experimental results from the samples.

3. Conclusions and next steps

First, we notice that the curve of FES, with respect to the focus point, is not symmetrical regardless the material, reaching higher values for negative positions. This can be translated in a loss of measurement range when the rugosity is 'positive' (meaning towards the objective).

With the Mirror target we should have had the best results with a FES variating from -1 to 1, instead we had just a variation of -0.4 to 0.3, meaning that we couldn't measure profiles larger than 20 micron. At last, it is important to refer that the repeatability should improve once the translation stage is substituted by one with a higher resolution.

These results were important to understand not only where the system needs to be improved and its limitations, but also the type of material the samples should be made of to test its profile. A bright specular surface would be the ideal, such as a mirror or a bright specular metal. By using a specular sample, the intensity of the light source doesn't need to be very intense, reducing the parasite reflections. On the other hand, by choosing a specular metal we are making sure that the spot over the sample surface is well defined. Diffuse samples can be used assuring that the rugosities are smaller than the spot. The formed spot should be uniform and diffusing light isotropically (which would not happen if the rugosities are the same scale size of the spot created by the objective).

In brief, with the developed prototype we obtained experimental results which showed that it is possible to discriminate FES values in steps of 5 micron for most of the samples, however within a reduced range when compared with the theoretical model. With these first results, by making a proper interpolation it is possible to make the profilometry of a surface – with the characteristics described above - that has its profiles with a maximum absolute heigh of 20 micron and with an uncertainty better than 5 micron.

On a last observation, although the resolution of the system is 5 micron, the software is able to discriminate at least 10 different images taken between a step of 5 micron, meaning that the prototype needs to be mechanical optimized to achieve an uncertainty of at least 0.5 micron.

The next step is to define better the curve of FES of the system by improving the range of work and its sensibility, before performing the profilometry of samples.

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