Master thesis Work

Development of a new Confocal Tracking sensor for shape measurement of optical surfaces

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ABSTRACT

In this thesis work, a new contact sensor applied to the shape measurement of optical surfaces is presented.

This contact sensor is based on confocal tracking technology. This technique consists on tracking the focus of the sample while it is moved along the horizontal axis at a constant speed. It is capable of providing nm level accuracy as required by state of the art optical designs.

Existing applications of such technology use an all-optical approach, which have advantages such as being non-contact technique but also some limitations such as the maximum slope measurable. The sensor developed in this work is designed to seamlessly integrate onto existing systems extending the maximum measurable slope to more than 60 degrees. Even though the sensor requires contacting the surface to operate, its force can be easily adjusted, thus making it flexible and adaptive to different samples and applications.

Keywords: confocal tracking, single point technique, contact objective, contact objective with tunable force, optical surface, shape measurement.

1. INTRODUCTION

Being on leading edge of the metrology field for optical surfaces requires both high accuracy and fast measurement speed. In order to reach these specifications, several companies have developed in the past different measurement technologies based either on non-contact techniques such as confocal tracking [1] [2], focus detection or pattern projection or on the well-known contact techniques such as the stylus profilometers or atomic force microscopes [3].

Non-contact techniques such as confocal tracking, developed and patented by Sensofar Tech S.L [1], consists on tracking the focus on the surface while it is moved along the horizontal axis at a constant speed. Since it is an image-based technique it is able to correct for the tracking errors present in single point technologies. It’s a fast and very accurate technique for the measurement of aspheric and free-form optics with additional advantage of being a non-contact technique, avoiding potential scratches on the sample. However, this technique has limitations such as that it is not capable of measuring local slopes larger than 35 degrees and the relatively short working distance between the microscope objective and the sample.

Contact techniques such as the stylus profilometers [4], which drag a stylus along the sample and monitor its position to obtain information on the surface profile are able to measure larger local slopes but have the drawback that they can easily scratch the sample. Moreover, sample alignment and navigation is quite difficult. AFM based stylus profilometers minimize surface scratching as they apply less force but are extremely expensive.

Given the drawbacks of the existing technologies, in this thesis work we focused on developing a new sensor, capable of overcoming the existing problems but keeping it simple in terms of design and using the same patented technology by Sensofar called “confocal tracking”.

1.1 NEW DEVELOPED CONTACT SENSOR

The main goal of this project has been developing a new sensor, called contact objective, which combines the advantages of both contact and non-contact technologies, while improving their limitations. But also fulfilling the key specifications for being competitive in the optical surfaces metrology field: high accuracy, high speed and non-sample scratching. The contact objective has been designed from scratch using CAD software\(^1\) to be seamlessly integrated onto the instrument called Plu Apex, which uses the patented technology from Sensofar called “confocal tracking”. This guarantees to achieve high accuracy and high speed. Using this contact objective makes it possible for the Plu Apex system to measure local slopes larger than 60° without scratching the sample thanks to the small and controlled amount of force applied on the surface.

2. WHAT IS ALREADY IN THE MARKET AND WHAT MAKE US UNIQUE

Since many years contact systems from Panasonic or Taylor Hobson have been the used in the dedicated metrology of 3D forms of lenses and molds [3].

The “Talysurf PGI” system from Taylor Hobson [5] has been a reference system for the measurement of forms, textures and dimensions since mid 80’s. It was developed in 1984, specifically for the precision bearing industry and until today, it is still widely used. Its working principle consists on dragging a stylus along the surface and to monitor its position as it travels across peaks and valleys from the surface using an inductive gauge\(^2\). The stylus is located at the end of a lever arm which may introduce measurement errors. This system uses a minimum measurement force of 20mN and it is capable of measuring local slopes up to 80°. Due to the fact of using an inductive gauge, its noise is around 4 nm under best circumstances. Furthermore, it is a big and heavy system and can be quite expensive in some of its configurations.

Panasonic has also a widely used contact system in the market called "UA3P" [6]. The working principle of this instrument is based on atomic force microscopy (AFM). In order to measure this system approaches an Atomic Force Prove (AFP) to the sample until atomic forces generate repulsion against the measurement surface and then a closed-loop system keeps this atomic force constant while the prove is dragged along the surface. This system works with measurement forces of 0.15-0.3mN, much lower than those in the Taylor Hobson system thanks to its AFP method. Because of the fact that it doesn’t use a lever arm and that it uses laser feedback encoders, its accuracy is extremely good and the measurement noise is smaller than that of the “Talysurf PGI”. However, this system can only perform measurements on sample with local slopes up to 60°. Moreover, this product is notably heavy and bulky and way more expensive.

The contact objective that is proposed in this work, improves the performance and overcomes the limitations of the existing products in the market. It is based on the “confocal tracking” technique patented by Sensofar Tech S.L. Its tunable measurement force and its precise determination of sample position, make this technique unique in terms of advanced measurement methods in the market. It has low noise thanks to its simple design, having no lever arm. Moreover, whereas the two systems presented use a

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\(^1\) Creo Parametric PTC software has been used for the Opto-mechanical design and simulation.

\(^2\) Electro-mechanical device that measures in two directions. A process unit records the amplitude and frequency of ondulations and converts the data into information about the roundness, shape or form.
constant measurement force, our design allows us to tune the measurement force between 4mN to 30mN\(^3\) and, hence, adjust it to each sample characteristics. Furthermore, this prototype measures with high accuracy and a fast speed as it is installed in Plu Apex system and it’s capable of measuring local slopes up to 75°. Finally, this prototype has been designed as a lightweight and balanced quality-cost device. It has the possibility of becoming a competitive alternative in the near future.

3. DESIGN OF THE CONTACT OBJECTIVE

![Figure 1 CAD design performed with CATIA V5 and CREO Parametric.](image)

The figures above show the design of the contact objective, which is composed by a 100X SLWD microscope objective (100) which images an internal mirror tilted for optimal performance (101). A key part of our design are two thin membranes with a thickness of 50 μm (104,105). These membranes hold the stylus shaft (103) and allow the optimal vertical movement of the contact tip (107) up and down. This contact tip is a small Rubi ball of 1mm diameter. Finally, there are two mechanical contacts to limit the displacement of the stylus shaft for safety reasons (102,106).

The stylus shaft with the contact tip at its bottom and the internal mirror at its top will either move up or down tracking the sample surface. This will translate onto changes of the best in focus point detected by the objective, which will allow the reconstruction of the surface.

Finally, it is worth to comment that this contact objective has been designed to be small, light and cheap in terms of manufacturing. However, it is necessary to say that our goal was to build a prototype in order to check the feasibility of the technology.

3.1 DESIGN OF THE INTERNAL MIRROR

In order to calculate the thickness of the membranes, the allowed vertical displacement \(\delta\) should be known. This will depend on the FOV size (which in turn depends on the objective used) and the tilting of the internal mirror. The maximum displacement will be the maximum allowed deformation of the membranes.

The optimum slope of the internal mirror can be calculated from the resolution of the Z position sensor which is 30nm/pixel and from the resolution of the CCD camera which is 768x576 pixels. Assuming that the CCD camera has 1000 pixels:

Maximum displacement (Whole FOV): \[ \delta = 30 \frac{nm}{pixel} \cdot 1000 \text{pixel} = 30 \mu m \]  \hspace{1cm} \text{Eq.1}

\(^3\) It is possible to tune the measurement force down to 0.1mN. However, after testing, it has been seen that this causes errors when tracking the surface because the contact tip is not able to follow the surface continuously. This effect is more appreciable when reaching high local slopes.
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Therefore, the allowed displacement of both membranes would be \( \delta = \pm 15\mu m \).

The tilt angle (\( \alpha \)) of the internal mirror can be calculated from the maximum vertical allowed displacement and the horizontal size of the FOV. Using a 100X SLWD microscope objective from Nikon, the FOV horizontal size is 128 \( \mu m \). Therefore, the angle \( \alpha \) of the internal mirror is:

\[
\tan \alpha = \frac{30\mu m}{128\mu m} \rightarrow \alpha = \arctan\left(\frac{30\mu m}{128\mu m}\right) \sim 13.5^\circ
\]

Even though the maximum vertical displacement calculated for the membranes could be \( \delta = \pm 15\mu m \), a security factor of 1.5 is taken in order to protect the membranes from damage. Taking this security factor, the allowed displacement is \( \delta = \pm 10\mu m \).

### 3.2 DESIGN OF THE MEMBRANES

In our contact sensor device, the internal membranes are a key part and need to be designed in order to achieve a desired performance. Given the diameter of the membranes, material characteristics and the maximum vertical deformation, the thickness of those membranes can be calculated analytically.

In our case, we have studied two different materials; stainless steel and aluminum. After consideration, “stainless steel” has been chosen for our design and following prototype.

Stainless steel ("Steel structural" ASTM-A36) has a Young’s module of \( E_{\text{steel}} = 200 - 210 \text{ GPa} \) and a Poisson coefficient of \( \nu_{\text{steel}} = 0.30 - 0.31 \).

Knowing that the density of the material (stainless steel) is \( \rho_{\text{steel}} = 7.85 \text{ g/cm}^3 \) and the geometry of the stylus shaft, it is possible to calculate the total mass by calculating its volume. We have approximated the real geometry to a simplified model of a cylinder, simplifying the calculus and giving a safer value. The thickness calculated will take into account a higher mass than the real one, ensuring that the membranes will not be damaged.

A cylinder approximation has been used to calculate the total mass:

\[
\text{Mass: } m = \text{density} \cdot \text{volume} = 7.85 \text{ g/cm}^3 \cdot \frac{1 \text{ cm}^3}{1000 \text{ mm}^3} \cdot \pi \cdot \left(\frac{3 \text{ mm}}{2}\right)^2 \cdot 51 \text{ mm} = 2.83 \text{ g} \quad \text{Eq.3}
\]

Finally, taking into account that the radius of the membrane is equal to 10mm, we have all information needed (mass, membrane radius, Poisson coefficient, Young’s module, \( \delta \)) for calculating the thickness of the membranes [8]:

\[
F_{\text{membrane}} = k \cdot \delta = \frac{16 \pi D}{r^2} \cdot \delta \rightarrow m = \frac{16 \pi E h^3}{12(1-\nu)^2 r^2} \cdot \delta \rightarrow h \sim 50 \mu m \quad \text{Eq.4}
\]

Wherein:

- \( F_{\text{membrane}} \) is the force applied on the membrane, \( k \) is the stiffness of the membrane, \( E \) is the Young’s module, \( \nu \) is the Poisson coefficient, \( r \) is the radius of the membrane, \( g \) is the gravity and \( h \) is the thickness of the membrane.

### 4. MEASUREMENT METHOD

The measurement method of the new contact objective is based on the principle of Confocal Tracking Technique [1] which was previously developed from the concept of slit confocal microscopy. In a confocal tracking profiler [7] a pattern of parallel slits is imaged.
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by a high numerical lens on the surface to be measured. Instead, in the contact objective, such slit pattern is imaged on the surface of the internal tilted mirror, which is located on the top of the stylus supported on the membranes.

The slits are projected parallel to the X axis. Only the central slit will be used for the measurement and the midpoint within the field of view along this central slit will be considered as the reference pixel (see fig 3 and 4). Side slits will be very useful for aligning the internal tilted mirror in the X direction. Such alignment is attained when the best focused pixels of the slits appear well aligned along the Y axis.

In a first step, the sensorhead holding the contact objective is moved down until the tip contacts the surface to be measured. After contact, the head continues to move downwards until the best in focus pixel of the central slit is positioned as close as possible to the reference pixel, which corresponds to a deformation of both membranes that doesn't have to be necessarily 0, but depends on the initial non-contact setting position (explained later on in detail).

Once we are at this initial position, the sample is moved along the horizontal X axis at constant speed while the sensorhead holding the contact objective is continuously moved along the vertical Z axis. This coordinated move is carried out in a way that the best in focus pixel of the central slit is maintained as close as possible to the reference pixel. This focus set point can be attained by using a PID closed loop autofocus algorithm. In this way, the contact objective is tracking the surface to be measured while maintaining almost constant the force between the tip and the surface all along the measured length.

While performing the tracking of the surface, a CCD camera acquires a series of frames of the corresponding fields of view at a constant frame rate (50 Hz). The CCD is triggering the reading of X and Z position sensors, so that a point \((x_i, z_i)\) is obtained for each frame. It is worth noting that this set of \((x_i, z_i)\) points would be the output of a measured surface shape given by a profiler based on a single-point technique.

However, it is well know that even the best and fastest closed loop autofocus has a residual tracking error, which can be acceptable if the goal would be to keep the best in focus pixel near the reference pixel. Nonetheless, this tracking error may be too high when
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surface shape measurements at the nm-level are being pursued. The confocal tracking method makes it possible to overcome this limit by correcting the height tracking errors.

The principle underlying the confocal tracking method is to correct the height $z_i$ of each measured point $x_i$. The corresponding tracking errors $\Delta z_i$ are obtained for each frame as the distance along the central slit between the best in focus pixel and the reference pixel (in pixel units) multiplied by the calibrated slope of the tilted mirror (in nm/pixel units), as it can be seen in Fig. 6.

Therefore, the shape of the optical surface being measured is obtained by building a 2D curve composed by the following points:

$$[(X_1, Z_1 + \Delta Z_1), (X_2, Z_2 + \Delta Z_2) ... (X_i, Z_i + \Delta Z_i)]$$

Eq.5

Wherein:

$(X_1, X_2, \ldots X_i)$ Refer to the measured points of the surface in the X axis; $(Z_1, Z_2, \ldots Z_i)$ refer to reading of the Heidenhain close loop in the z axis corresponding to each $X_i$ position and $(\Delta Z_1, \Delta Z_2, \ldots \Delta Z_i)$ refer to the "height tracking errors" in z for each different position. These correction differentials can be converted from pixel units on the CCD images into height units on the optical surface of the sample being measured, taking into account the real magnification of the objective being used; $Z_i + \Delta Z_i$ Refers to the corrected height for each $X_i$ position.

It is obvious that the shapes obtained with the confocal tracking technique will be much more accurate than those obtained with single-point based techniques, because the representation of the surface is composed entirely of points with corrected tracking errors.

5. TUNING OF THE CONTACT FORCE

The contact force between the tip and the surface during the measurement can be tuned very easily. When there is no contact between the tip and the surface, the membranes are supporting the complete weight of the stylus and therefore their deformation will be the maximum (approximately 15 μm with the current design). Under these non-contact conditions we can adjust the distance between the tilted mirror and the objective. If the probe holding the stylus is moved down in relation to the objective (see Fig. 1), then the slit pattern will focus on an upper height of the mirror and the best in focus pixel will be shifted to the right part of the field of view. We refer to such position as "non-contact setting position".

In Figure 5 we can see two different examples of tuning conditions. In one of them the probe was moved down until the "non-contact setting position" was shifted to the rightmost part of the field of view (pixel #333). With this setting, when the sensorhead is
moved downwards until reaching the initial measurement position (in which the best in focus pixel is positioned as close as possible to the reference measurement point corresponding to pixel #0), the resulting contact force will be approximately 32 mN and the deformation of the membranes will be almost zero (blue lines in Fig. 7).

In the second example, the probe was positioned so that the "non-contact setting position" is pixel #167. In this case, when the sensorhead is moved downwards until reaching the initial measurement position, the resulting contact force will be approximately 17 mN and the deformation of the membranes will be approximately 6.5 μm (red lines in Fig. 7).

Thus, the closer is the "non-contact setting position" to the reference measurement position (reference pixel), the smaller will be the contact force and the greater will be the deformation of the membrane during the measurement. Experiments have shown that the smallest contact force that can still work properly is 4 mN, which is attained when the "non-contact setting position" is placed around pixel #80.

6. BALL SHAPE CORRECTION

When measuring the profile of a surface, the measured radius doesn't match the nominal one but it is always larger; this is due to the fact that the contact point between the ball tip and the surface depends on the local slope as seen in figure 8. The ball tracking the surface introduces an error which depends on the radius of the ball itself and the local slope being measured. This has been modelled and compensated by a software algorithm.

![Diagram of ball shape correction](image)

**Figure 6** Detail of the measured radius with respect to the real one. Tip tracking error depends on the local slope.

The local slope is calculated every 10 pixels in order to find which is the z correction for the specific local slope. The z correction \( \Delta z \) factor is calculated according to the following expression:

\[
\Delta z = r \cdot \left( \frac{1}{\cos \alpha} - 1 \right)
\]

7. RESULTS

In this section, different measurements performed using the contact objective technique are presented. In order to measure the accuracy of this contact objective, a set of measurements on a calibrated spherical ball were performed.

Figure 7 shows the measurement of a ball standard and the best fit radius raw residual error in comparison with the best fit radius error correcting the height tracking error.

When the height tracking error correction is applied the noise obtained is smaller and the curve shows smoother peaks in comparison to the raw data. This effect is even larger when the measurement speed is larger. In the last subplot the same residual profiles are shown with a 0.08μm roughness filter applied in order to extract the measurement noise.
Figure 7 Measurement of a calibrated ball standard. Measured Profile and the best fit residuals. Measurement speed: 0.5mm/s. Forces applied: 4.5mN. Green curve (centroid correction) VS red curve (no centroid correction). Rms (centroid correction) = 6, Rms(raw data) = 7 nm

Figure 8 Measurement of a calibrated ball standard. Measured Profile and nominal radius fit residuals. Measurement speed: 0.1mm/s. Force applied: 30mN (non-contact setting position pixel #308). Nominal radius 22.5035mm. Best-fit radius with radius correction: 22.5334mm. Best-fit radius using raw data:

Figure 9 shows a comparison between a measurement applying a radius correction of the ball with respect to raw data measurement. The effect of the Rubi ball tracking the sample is clearly seen. The measurement has been performed on a calibration ball standard performing a symmetrical 20mm range measurement through the apex of the sample with a speed of 0.1mm/s.

Figure 9 shows a study of the membrane lateral deformation (or stylus shaft deformation) when different forces are applied on the sample. It has been interesting to measure a range from the apex to a slope angle of 61 degrees, where the maximum deformation will take place. As can be seen in the figure, the membranes behave almost identically regardless of the force applied (between 4.5 and 30mN). A third plot shows the local slope of the surface.

Figure 12 Comparison of a measurement of a calibrated ball standard taken with APEX (optical system) and contact sensor. Measured Profile and best fit residuals. Measurement speed: 0.5mm/s. Green curve (Contact Sensor) VS red curve (APEX). Rms (APEX)=125nm, Rms(Contact sensor)=95nm
The measurements have been performed with a speed of 0.3mm/s and with the different tunable forces of 23.5mN (red color), 13.5mN (green color) and 4.5mN (blue color). Also, both corrections (height tracking error + radius) have been applied for the measurement. It is also important to note that around 55 degrees appears a repeatable peak for all forces caused by a possible imperfection in the shape of the Rubi ball. Table 1 shows a summary of different measurements performed with different tunable forces and speeds.

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Table 1 Different measurements of a calibrated ball standard using different speeds and tunable forces

It is important to say that the different radiuses measured with different forces are not comparable between them because it was not possible to measure exactly the same part of the sample after force adjustment. However, it is worth to say that the radiuses measured are very repeatable for each tunable force and that the “rms” of the measurement increases as the speed increases.

Figure 10 shows a comparison between the contact objective and the APEX system. As can be seen, performing the measurement with the APEX higher levels of noise are obtained.

8. CONCLUSIONS

A new contact objective technique has been developed for the measurement of optical surfaces. Different tunable forces can be applied when performing the measurements.

It has been proved that this contact sensor measures optical surfaces that are not able to be measured with non-contact systems. Moreover, this device can measure local slopes higher than 60 degrees and having a shape error smaller than 100nm (given that the error introduced by the Rubi ball is accurately modelled).

Also, the elastic behavior of both membranes has been studied. The force corresponding to each deformation of both membranes has been calculated matching the analytical calculations and having a linear response and quick return to its original position, no matter which is the deformation direction. In order to guarantee that the membranes cannot get easily damaged, a security test has been performed making sure that lock washers do their job. See Annexes A (elastic membrane behavior) and C (security limit test).

One conclusion of the test performed is that both membranes deform almost identically for different tunable forces, tested between 4.5 and 31mN when reaching higher local slopes (figure 11).

The first measurements performed on a ball standard were always giving a radius roughly 0.5mm larger than the nominal radius. This is because of the error introduced by the
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shape of the Rubi ball. The shape error introduced by the contact tip has been modelled and removed by software algorithms. It is worth to note that the shape error is still not 0 when applying the radius correction; we have assumed that the Rubi ball has a 0.5mm radius but this value has some tolerance which has not been taken into account.

Further, we have been able to measure a calibrated ball standard using different speeds and different forces applied on the surface. Another conclusion is that the noise increases with speed no matter the force applied on it.

In addition, the repeatability of this contact objective has been proved to be very good as well as the possibility to track surfaces at quite high measurement speed (1-2mm/s) using a tunable force, avoiding scratching on the surface and having more flexibility to adapt to different samples and applications.

Having seen the great potential of this contact sensor, one might think to introduce it to the market. However, some improvements would be required before such as making it more robust, adding the possibility to tune the forces automatically by software.

Also, the way the contact objective is assembled and set for starting the measurement is not easy. This would need to be modified if we want to offer this contact sensor as a commercially available device.

From my point of view, this has been probably the best project I have ever been involved in, where I had the opportunity to build "something" from scratch, comparing analytical with experimental results and facing problems that at the beginning one does not expect.

REFERENCES