euspen's 20th International Conference & Exhibition, Geneva, CH, June 2020
www.euspen.eu

Small footprint high-speed optical 3D profiler

Pol Martínez, Carlos Bermudez, Manel Moya, and Roger Artigas

Sensofar Tech SL, Barcelona, Spain

pmartinez@sensofar.com

Abstract

In surface characterization at the micro- and nano level, the most used non-contact techniques are Imaging Confocal Microscopy (ICM), Coherence Scanning Interferometry (CSI) and Focus Variation (FV). Each measuring technology has its benefits and disadvantages. Whereas CSI is the best technique to measure optically polished samples, it does not perform well in rough surfaces due to its inability to recover signal from high slope regions. FV performs, however, very well with rough surfaces but lacks repeatability on smooth samples, and its repeatability depends on the surface roughness. This has improved recently by the introduction of Active illumination Focus Variation (AiFV). Confocal is besides a versatile technique than can retrieve data from surfaces ranging from smooth to rough with a repeatability down to 1 nm, although needs to do in-plane scanning.

However, all the mentioned techniques rely on scanning the surface through the optical axis. Measurement speed depends not only on the acquisition framerate and image processing time but also on the mechanical dynamics.

In this paper we propose a compact optical 3D profiler that can measure at higher speed thanks to an increase of camera framerate, lower mass and a novel confocal technique that does not need in-plane scanning. This has been achieved by reducing the overall optical path length, which challenges narrower focal lengths and thus higher optical aberrations. The system scans only the objective lens instead of the whole sensor head with a high-speed, 4 mm travel range miniature translation stage. As the sensor scans can be made continuously oscillating the objective lens, real-time 3D topographies can be obtained.

Keywords: Interferometry, Metrology, Microscope, Surface

1. Introduction

Nowadays, Industry 4.0 takes us to more complex, precise, and digitized manufacturing processes. Quality control is more important than ever and throughput cannot be affected by QA.

Regarding surface engineering, there is also the trend to integrate in-line sensors to be able to provide feedback for close-loop manufacturing. This tendency is demanding narrower, lighter and faster sensors.

The typical surface characterization technologies are Imaging Confocal Microscopy (ICM), Coherence Scanning Interferomety (CSI) and Focus Variation (FV). For every kind of surface, one technology may perform better than another one. Confocal is probably the most versatile technique measuring from optically smooth to rough surfaces that yields high lateral and vertical repeatability, up to 1 nm. All these techniques scan the surface along the Z axis.

Nevertheless, Confocal technique needs to do in-plane scanning, limiting the acquisition speed compared to CSI or FV for the same framerate.

In this paper we present a compact Confocal 3D profiler that scans the objective lens instead of the full sensor head, thus improving the sensor dynamics and the scanning speed. The head also integrates a high framerate camera (1000 fps), a short optical path length to reduce the head size, and a novel confocal technique that does not suffer from in-plane scanning.

Together with GPU processing and oscillating the Z scanner non-stop, confocal images are calculated in real-time, therefore obtaining 3D topographies every second.

The rest of the paper is organized as follows: in section 2, the methodology is described. Section 3 shows the results on real measurements implementing the explored method whereas section 4 presents the conclusions.

2. Methodology

In most of the optical profilometers the technologies used are CSI, ICM or FV. Whereas CSI and FV only need a scanning along the Z axis, ICM needs a scanning in Z axis but also in-plane scanning, entailing a higher measurement time.

The opto-mechanical design of the system we have developed has been optimized to measure with any of the mentioned technologies, to acquire data with very high scanning rate, and everything with a footprint as small as possible. In order to be compatible with bright field measuring techniques such as CSI and at the same time with structured illumination techniques, such as Active illumination Focus Variation (AiFV) and single image patterned confocal, a dual illumination scheme is adopted. Two LEDs illuminate two conjugate field diaphragms; one of them with a glass mask with a predefined pattern, and the second one with a clear aperture. The pattern we used is a checkerboard such as the one proposed in [1], which allows to recover an optical section by a local gradient focus operator, and at the same time an optical section equivalent of a Confocal Image by the use of the Hilbert transform [2].

Figure 1. Lateral section of the optical profiler. Green lines indicate the light path of the illumination crossing the checkerboard pattern glass, whereas the white lines show the one through the clear aperture.

On the latter technique, each column of the registered image from the sample illuminated with the structure of the checkerboard has a periodic signal similar to a sinusoid. If we split each column, the intensity distribution can be written as:

$$I(x) = A(x) + B(x) \cdot \cos(kx + \phi) \quad (1)$$

where A is the DC component (the image without the structured pattern), B is the modulation of the pattern, k is the wavenumber corresponding to the projected frequency, and ϕ its phase. By means of the Hilbert transform, only with signal processing methods, we can shift the phase of the periodic pattern by π/2. The intensity distribution will be:

$$I_H(x) = B(x) \cdot \sin(kx + \phi) \quad (2)$$

and the pattern modulation:

$$B^2(x) = \left(I(x) - A(x)\right)^2 + I_H^2(x) \quad (3)$$

If we repeat this process column by column of the image we can recover the modulation of the whole image, which equals to the optical section for a given scanning position of the sample. The DC term in equation 1, A(x), can be recovered by the use of the second illumination channel with the clear aperture, meaning the use of two images to recover the optical section. A faster method is recovering the DC term by filtering out the main frequency pattern in the Fourier space. This method requires only the use of a single image to recover the optical section with the drawback of being less precise and leaving residual artifacts on the recovered optical section. Nevertheless, those artifacts are small compared to the height of most technical surfaces and its impact on accuracy is negligible.

The vast majority of microscopes are designed to have a tube lens with a focal length of 200 mm, making optical profilers to be large in the vertical direction. To achieve small footprint, we have designed a 50 mm tube lens made from 6 lenses in 4 groups which is used as a field lens simultaneously for the illumination and observation. The whole optical system is infinity corrected and complies with Köhler illumination design. In combination with such short tube lens, we selected a camera with 4.8 micron pixel size and up to 1.3 Million pixels at 240 fps, and achieving 1000 fps at a resolution of 640x480.

For CSI measurements at 9X scanning sampling and 1000 fps, we scan at more than 650 micron/second. Such high speed is achieved with the use of a single objective scanning linear stage from Dover Motion (Boxborough, MA, US), model DOF-5, with 5 mm travel range and 2.5 nm closed loop sensor.

Figure 2. Dimensions of the optical profiler compared to a 33 cl can.

3. Results

We analysed the performance of the proposed system in comparison to a commercial confocal 3D optical profiler.We measured a roughness standard from NPL (UK), model AIR B40 with a nominal roughness value (Sa) of 0.79 micron. We used a Nikon 20X 0.45 NA objective. Figure 3 shows the confocal 3D topography (left) and the result from our system (right). Table 1 shows the roughness parameters for both results.

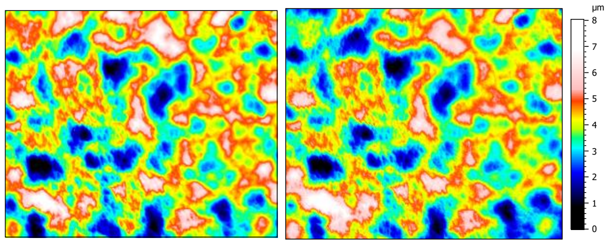

Figure 3. Topography of AIR B40 roughness standard measured with (left) a commercial confocal system and (right) our proposed method. The field of view is 0.84 mm x 0.71 mm.

Table 1 Roughness parameters of NPL AIR B40.

Parameter	Sa (µm)	Sq (µm)	Sz (µm)
Nominal	0.791	1.007	7.336
Standard confocal	0.837	1.067	7.798
Proposed method	0.828	1.053	8.043

In our proposed method, the topography shows some periodic artifacts with respect to the confocal topography, but as the shape of the surface is greater than these artifcats, the roughness parameters do not differ significantly between the two results. The deviation to the nominal values is due to a lower field of view, that causes that not all the frequencies are present in the image. We noticed a measurement reduction time by a factor of 16 in comparsion to the commercial confocal 3D profiler due to the suppression of in-plane scanning and a higher camera frame rate.

4. Conclusions

A high-speed optical 3D profiler has been built for measuring with multiple techniques, allowing to measure a vast range of samples. A higher frame rate camera and moving only the objective lens instead of the whole system allow higher dynamics on the Z scanning. The use of signal processing tools allows to remove the in-plane scanning in ICM without compromising the performance.

References

[1] Bermudez C, Martinez P, Cadevall C, and Artigas R. “Active Illumination Focus Variation”. Proceedings Volume 11056, Optical Measurement Systems for Industrial Inspection XI (2019).

[2] Hoffman Z, and DiMarzio C. “Single-image structured illumination using Hilbert transform demodulation” J. of Biomedical Optics, **22**(5), 056011 (2017)