Measurement of optical surfaces by Structured Illumination MACROSCOPY – with correction of the retrace error

Zheng Yang, Alexander Bielke, Evelyn Olesch, Philip Dienstbier, and Gerd Häusler

Institute of Optics, Information and Photonics, University of Erlangen-Nuremberg

mailto:zheng.yang@physik.uni-erlangen.de

SIM is a proper method to acquire the 3D-topography of smooth and rough surfaces. As we scale up this principle, it turns out that SIM for a large FOV exhibits extreme difficulties: the unavoidable optical aberrations introduce retrace errors, which cannot be easily removed by calibration. In this paper, we present a calibration strategy and a hybrid 3D sensor to overcome these errors.

1 Introduction

Structured-**I**llumination **M**icroscopy (**SIM**) is a powerful technique for either acquiring three- dimensional data of technical (rough and smooth) surfaces [1,2] or for the improvement of the diffraction-limited axial and lateral resolution of fluorescence microscopy [3]. A measuring uncertainty better than 10nm and a high angular dynamical range >±70° was achieved at technical surfaces [4].

These useful features suggest to scale-up SIM for “Structured Illumination MACROSCOPY”, in order to measure large objects, such as wafers, lenses, cutting tools or sealings. We have built such a macroscopic “SIM” [5] and demonstrated that the scaling up of SIM is principally possible. However, it turns out that Structured Illumination MACROSCOPY for a large field of view exhibits severe difficulties: first: the unavoidable optical aberrations cause big global measuring errors and at the same time a bigger local measuring uncertainty.

For a proof of principle experiment, a trade-off between field size and local uncertainty has been chosen. With a field size of 4.8 by 3.6 mm^2 a local measuring uncertainty of 100 nm could be achieved. To measure a high precision optical surface, we also have to care about the systematic (global) error: In this paper we will investigate the trueness of Structured Illumination Macroscopy and introduce a useful calibration method.

2 Analysis of the global error

As interferometry, SIM is a height measuring principle. Height measuring is comparing the object shape with an etalon. In SIM, the etalon is just the scale of the translation stage and the focal plane of the objective. The systematic error of SIM is dominated by the shape of the objective’s focal surface. Unfortunately, this surface is strongly dependent on the path of rays through the aperture. This path will be field dependent and slope dependent. If we want to avoid a specific reference etalon (as is commonly used in interferometry) we have to overcome this problem. Figure 1 illustrates the problem.

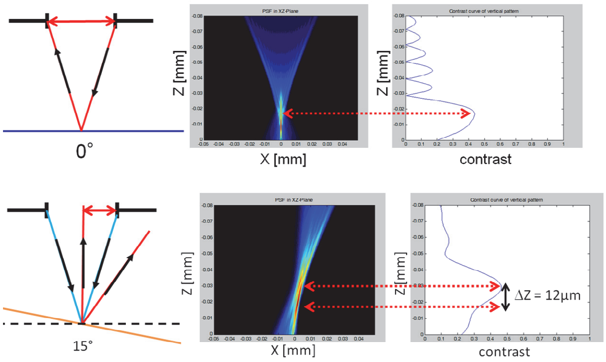

Fig. 1 *Simulated 3D-PSF in the xz-plane of the objective in presence of (only) spherical aberration, and the corresponding contrast curve C(z) at two tilt angles of 0° and 15°. Top: The tilt angle is 0°. The peak of the contrast curve displays the best focus position. Bottom: At a tilt angle of 15°, spherical aberration leads to 12µm shift of the best focus position.*

The aberrations lead to errors equivalent to the retrace errors in interferometry. They are more severe in a macroscopic SIM than in a microscope.

3 Experimental verification of retrace error

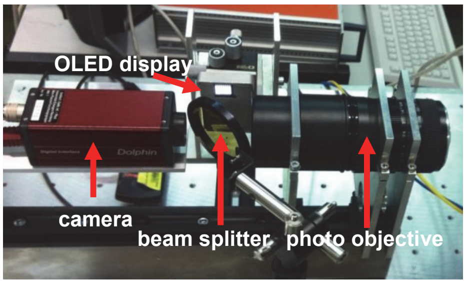

Fig. 2 *. Setup of **S**tructured **I**llumination **M**ACROSCOPY.*

We built a structured illumination macroscope as described in [5], using photographic lenses with F-number 0.95 (as shown in Fig. 1). In order to measure the angular dependent measuring error, we used a precision half sphere with a radius of 5mm as the sample under test.

The measuring error is calculated by comparing the measured height with the design data. It is shown in Fig. 3. The peak-to-valley error amounts to 46µm, which displays the difficulty of the problem.

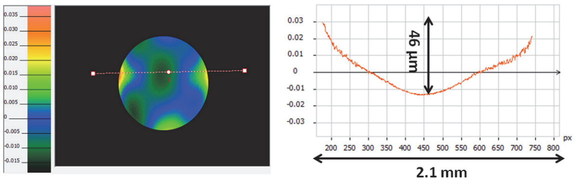

Fig. 3 *. Left: Deviation of the measured height of the half sphere from the design data. The angular dynamical range is: ±12°. Right: cross section of the maximum peak-to-valley error is 46 µm.*

4 Calibration strategy

The calibration procedure is sketched as follows:

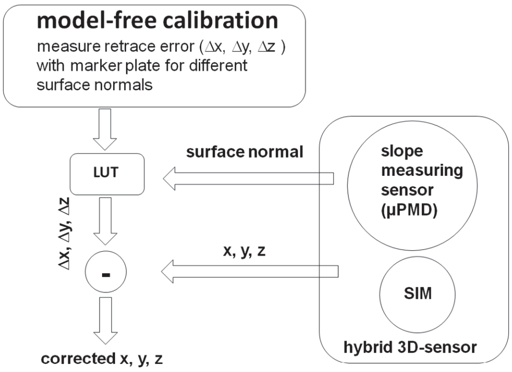

Fig. 4 *Scheme of the new calibration strategy for compensating the retrace error in macro-SIM.*

In order to avoid a (unnecessarily complicated model) we choose to develop a model-free calibration strategy. The key step is to precisely determine the retrace error for a sufficiently large set of field points and surface normals, within the system's measuring field and angular dynamical range. For this purpose we use a marker plate with 10 x 8 circles and tilt it to 60 controlled slopes. By comparing the measured position of the markers with known positions obtained from photogrammetry, we can calculate the retrace error at discrete lateral and angular positions. Subsequently, a 4D-Look-Up-Table (LUT) is generated by interpolation, to get the re-trace error for each point in 2D-space and for the two tilt components.

Since the LUT is a function of pixel coordinates and surface normals we combine SIM with a slope measuring principle, such as microdeflectometry (µPMD) [6]. The output of the LUT is a correction map, to be subtracted from the measured data.

5 Results

As a proof of concept, we have calibrated the system using the half sphere shown in Fig. 3. The deviation of the measured data after calibration is shown in Fig 5. Essentially due to imperfections of the mechanical mounts (two degrees of freedoms are necessary!) and the trueness of slope data the retrace error could only be reduced by factor of two. But we expect much room for improvement by improving the mechanics and quality of slope data.

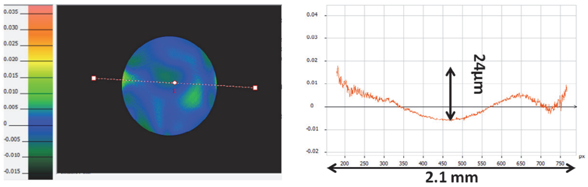

Fig. 5 *Re-trace error after calibration according to Fig. 3. The error is reduced by factor of two compared to the uncalibrated sensor. We aim for a measurement error of 1µm, by improving the mechanical mounts and using new method to calculate the slope.*

6 Acknowledgement

We kindly thank the DFG (HA 1319/13-1) for supporting this project.

References

[1] K. Engelhardt and G. Häusler: “Acquisition of 3-D data by focus sensing“ in *Appl. Opt., Vol. 27, No. 22*: 4684-4689 (1988)

[2] M. A. A. Neil, R. Juskaitis and T. Wilson: “Method of Obtaining Optical Sectioning by using Structured Light in a conventional microscope” in *Optics Letters. Vol. 22, No. 24*: 1905 (1997)

[3] M. G. L. Gustafsson, L. Shao, P. M. Carlton, C. J. R. Wang, I. N. Golubovskaya, W. Z. Cande, D. A. Agard and J. W. Sedat: “Three-Dimensional Resolution Doubling in Wide-Field Fluorescence Microscopy by Structured Illumination*”* in *Biophysical Journal Vol. 94:* 4957-4970 (2008)

[4] C. Kranitzky, C. Richter, C. Faber, M, C, Knauer and G. Häusler: “3D-microscopy with large depth of field” in *DGaO-Proceeding*: A12 (2009)

[5] Z. Yang, Ph. Dienstbier, A. Bielke, M. Vogel, Ch. Faber and G. Häusler: “Full-field macroscopic measurement of specular, curved surfaces with SIM” in *DGaO-Proceeding*: A6 (2011)

[6] G. Häusler, C. Richter. K. H. Leitz and M. C. Knauer: “Microdeflectometry- a novel tool to acquire three-dimensional microtopography with nanometer height resolution” in *Optics Letters Vol. 33, Issue 94: 396*-398 (2008)