Tuning Structured Illumination Microscopy (SIM) for the Inspection of Micro Optical Components

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We discuss the impact of field curvature on the global accuracy of structured illumination microscopy. Our analysis shows that the systematic errors due to field curvature depend on the slope of the specular sample if observation and illumination display different focal shells. We avoid this by a modified “common path” setup. It reduces the global shape deviations down to ± 150 nm.

1 Introduction

With the concept of "structured illumination microscopy (SIM)" it is possible to quantitatively acquire the 3D-topography of rough and smooth surfaces with extremely high longitudinal resolution (better than 10 nm for smooth surfaces) [1]. SIM is incoherent, information efficient and needs simple technology. By means of a high aperture the system is furthermore capable of measuring steep slopes up to 50 degrees, even for smooth objects.

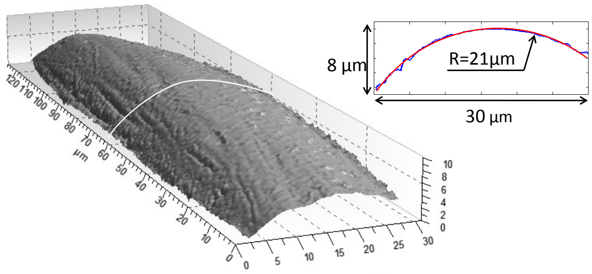


Fig. 1 *SIM data (50x / 0.80) from a touch probe tip. The lateral and longitudinal scales are identical to display the true angular dynamical range*

These features make the sensor attractive to measure micro optical components. Optical components, however, often require a global accuracy better than $\lambda/4$. To meet this requirement, systematic errors of the sensor must be compensated for. As for all focus sensing methods, a major systematic error of SIM is induced by field curvature because the so called object “plane” acts as the reference for height measurement. If this object plane is distorted by field curvature to an object shell the measured height data will enclose systematic deviations corresponding to the shape of the object shell. Typically such systematic errors can be treated by a simple calibration process: an object of known shape (e.g. a planar mirror) is measured; the resulting deviation of the global shape is saved as a null offset to be subtracted from every further measurement. For specular samples, however, we found that such a calibration process is not perfect. For specular objects the deviations induced by field curvature can be separated into two contributions: One that is independent of the object slope thus it can be compensated for by the calibration process given above. The other one, however, depends on the slope of the measured object point. This would require a self-consistent algorithm for compensation. To avoid this we investigated the underlying mechanisms. This led us to a modified setup that decreased the slope-dependent deviations to a measure much smaller than the field curvature.

2 Sensor principle

An incoherently illuminated grating is projected in the object plane of a wide field microscope (see fig. 3 a). While the object is scanned mechanically in axial (z-) direction the contrast of the illumination pattern is recorded. An object point yields a maximum of contrast if it is in focus [2]. Hence, the object height can be evaluated by localizing the z-position of the contrast peak.

The determination of the contrast in each pixel is done by controlled variation of the illumination pattern as suggested by Neil et al. [3].

3 Systematic errors

In the ideal sensor model the grating is projected exactly into the object plane. Thus the pattern appears with maximum contrast when an object point is in focus. Due to field curvature, however, the matching of the object shell and the projection shell can be achieved only in a small portion of the whole field of view. Figure 2 sketches a small detail of the microscope focus, where object shell and projection shell are displaced. For a specular object, maximum contrast is now obtained if the object point is between object shell and projection shell. Consequently the object appears blurred in this position. And even worse: the center of this blur spot changes position

if the object is tilted. This leads to a systematic error that depends on the slope of the object. The compensation of this effect is hardly possible.
To prevent this, the displacement of the projection shell must be avoided. Therefore it is essential that the two shells are of the same shape. However, they might still be curved—as long as they are equally curved—since the curvature of two matching shells can be easily compensated for by calibration with a planar calibration mirror (as given in the introduction).

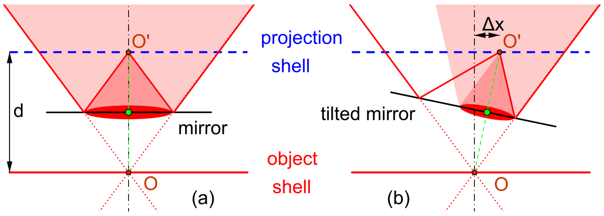
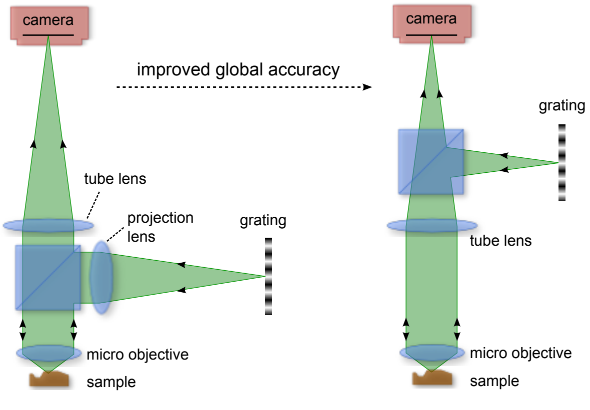


Fig. 2 *Detail of the microscope focus, comparing a non-tilted specular object surface (a) to a tilted one (b): The point O is the conjugate of a point on the camera chip. It is mirrored to O' by the specular object. The solid rays mark the observation aperture. The filled area displays the cone that is effectively illuminated due to the limited aperture of illumination. For a given displacement* d *of the projection shell, the center of the blur spot on the object moves laterally if the specular object is tilted ((a)→(b)). This leads to systematic errors that depend on the slope of the specular sample under test.*

4 Improved setup

Our modified setup is given in figure 3b. This “common path” setup will ensure that the curvatures of the object shell and projection shell are the same since they pass the same optical elements.



(a) typical setup (b) common path setup

Fig. 3 *Modification of the setup: (a) typical setup: field curvature of observation and projection is in general different due to different optical elements. (b) “Common path“ setup: the tube lens is also used for projection. This leads to equal field curvature for observation and projection, finally resulting in a better global accuracy.*

This creates the necessary preconditions for the matching of the two shells, but still requires proper adjustment of the grating with respect to the camera chip. This is achieved by employing deflectometric mechanisms [4]: The part of the grating that is imaged on a given camera point changes if a flat mirror is tilted (see Δx in fig. 2). The magnitude Δx of this change is proportional to the distance d between object shell and projection shell. Since the lateral position on the grating is encoded in the phase of the sine pattern it is an easily accessible measure for the displacement of the two shells.
As a test for the global accuracy of the improved setup, we measured a planar mirror that was tilted by 10 degrees. The deviation of the measurement from the required shape can be seen in figure 4. Although the setup has a field curvature of about 1.2 µm the remaining deviations are below ± 150 nm.

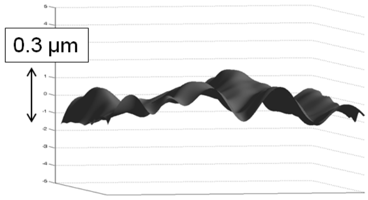


Fig. 4 *Deviation from the required shape for a 10 degree tilted mirror. The setup with a 20x / 0.45 micro objective has a field curvature of 1.2 µm.*

5 Summary

Field curvature introduces systematic errors in the height data of SIM. However, a global accuracy better than the inevitable degree of field curvature can be achieved by a simple calibration process if there are no systematic error contributions that depend on the slope of the object. This requires a proper matching of object shell and projection shell over the whole field of view. We achieved this by a “common path” setup with equal field curvatures for object shell and projection shell. After the setup was adjusted by taking advantage of deflectometric mechanisms the remaining global shape deviation of a 10 degree tilted mirror was below ± 150 nm for a 20x / 0.45 micro objective with a field curvature of 1.2 µm.

References

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