Extended Depth of Field Microscopy for Single Shot 3D Surface Profiling

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Abstract: We report a computational microscopy technique for 3D surface measurements with an extended depth-of-field. Using two independent cameras, it enables fast and robust extended-range topographic surface measurements from only a single pair-shot.

1. Introduction

The most common and well established techniques for 3D surface profiling are imaging confocal microscopy, focus variation, and coherence scanning interferometry [1]. These techniques are all implemented using a traditional microscope equipped with a high-precision z-stage. They are based on a common principle: the surface to be measured is axially scanned whilst a signal sensitive to the presence of the surface is computed from the acquired images. This through-scan signal, called axial response, is used to reconstruct the 3D surface under inspection by localising its maximum peak at each pixel.

The requirement for measuring the axial response has two obvious implications: measuring a sample requires a complete scan (i.e. through the considered axial range), and the sample needs to be positioned within the scanning range (often requiring an auto-focus to be performed beforehand). Besides, a high-precision z-stage is required because the final measurement precision is directly determined by the precision of the stage.

Here we report a computational microscopy technique for 3D surface measurements that is capable of reconstructing a surface topography with a single camera shot, therefore dropping the need for scanning. Furthermore, the technique extends the native depth-of-field of the microscope objective by an order of magnitude, and so also dropping the requirement for auto-focusing to some extent. The technique is based on Complementary Kernel Matching (CKM) imaging [2], and we report here an implementation based on two independent cameras, and a novel calibration and reconstruction algorithm that makes the method robust for surface profiling.

2. Methods and results

The optical layout of the technique is shown in Fig. 1. The key element is a refractive phase mask installed at the back aperture of the objective. The function of the mask is to modify the imaging point-spread function (PSF) of

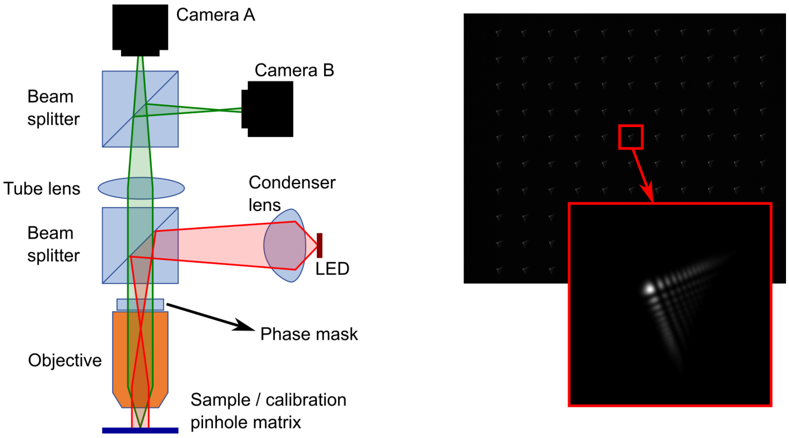

Fig. 1. Layout of the optical system and example image of the pinholes matrix.

the objective, through a cubic phase profile, which creates a PSF that translates with defocus. This is combined with a pair of cameras located at different focal points, as shown in Fig. 1, such that the translation between images can be used to uniquely determine a depth map of the sample. The calibration is based on the measurement of a matrix of sub-diffraction pinholes that enables to (a) segment the field-of-view (FOV) in small regions, and (b) characterise the 3D-PSF of the system at each FOV through an axial scan.

The reconstruction algorithm exploits the fact that, following deconvolution of the images using the measured PSFs, a non-zero disparity is produced when there is a mismatch between the depth of the sample and the depth of the measured PSF used for deconvolution. This is because the FOV is segmented into small regions, and so there is no local distortion between the image windows, except for a global rotation and magnification between the cameras, that needs to be corrected for and can be obtained from the images of the pinholes mask. This global rotation and magnification appear from the fact that the cameras can generally be slightly rotated between each other, and the fact that the system might not generally be perfectly image-space telecentric, respectively.

The 3D surface reconstruction is performed independently at each segmented FOV. The acquired image pair is deconvolved using a series of PSFs, that are measured through the working axial range as a one-time calibration. Determination of sample's height follows from identification of the PSF pair that produces the deconvolved image pair with the highest match. We compute this by: 1) deconvolution of the image pair, 2) application of global rotation and magnification to one deconvolved image, 3) calculation of a per-pixel metric based on the subtraction of the images, 4) selection of depth associated to the PSF pair with lowest metric at each pixel.

Surface topography measurements are shown in Fig. 2 of parts of a coin using a 20×/0.45NA objective, obtained from a single pair-shot. Note that the measurement range extends to approximately 100μm, whilst the native depth of field of the objective is approximately 2.3μm. Reconstructions in Fig. 2 are the combination of the colour-coded depth map and the extended depth-of-field intensity image.

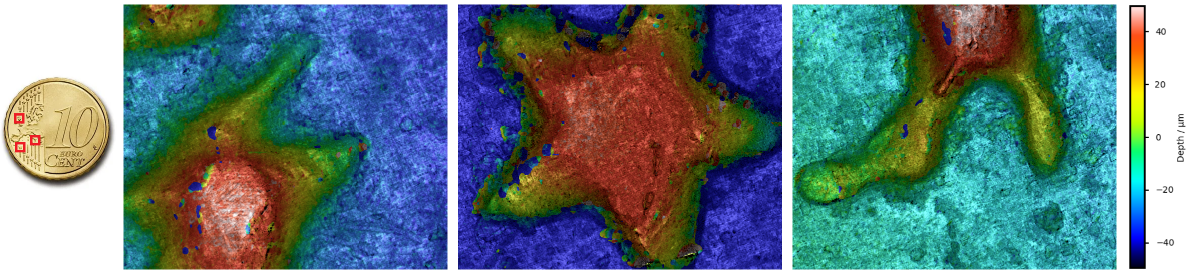

Fig. 2. Single-shot topography measurements performed on a coin, using a 20×/0.45NA objective. Reconstructions include depth measurements combined with intensity images.

3. Conclusions

We have reported a CKM implementation optimised for surface metrology. The implementation is based on the use of two independent cameras, installed at replicated image paths using a beam splitter, and with a relative defocus between them. The implementation benefits from a novel calibration and reconstruction algorithm based on measuring a matrix of pinholes, that simplifies the calibration and operation of CKM.

We have shown 3D surface reconstructions that extend 100μm using a 20×/0.45NA objective only from a single camera pair shot. This enables fast and scanless topographic measurements, and relaxes the demand for accurately positioning the sample (removing the necessity for auto-focusing).

The metric that is calculated during reconstruction is based on the local intensity mismatch between the recovered images, and therefore it relies on local intensity variations. This means that the lack of image texture would not produce an identifiable metric minimum, preventing to measure depth. Similarly, selecting the absolute minimum of the metric across the axial range is prone to errors that produce visible measurement artifacts, and although we incorporated post-processing algorithms based on local averaging to suppress them, some artifacts remain, as can be observed in Fig. 2. More elaborated post-processing of the metric would potentially improve results and further suppress such artifacts, which is a subject for future work.

References

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