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A new 2D-self-calibration method with large freedom and high-precision performance for imaging metrology devices

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Abstract
When calibrating 2D (or 3D) metrology systems you need to rely on a traceable artefact for the calibration. However if the system you intend to calibrate has smaller uncertainties than the uncertainty of the reference artefact, the uncertainty of the instrument will be dominated by the artefact and not by the instrument. The only way to reveal the performance of the instrument is then to use self-calibration, i.e. a calibration without any externally verified references, except a 1D traceable measurement between two points on an artefact. Already in 1997, Mikael Raugh developed the rigorous mathematics for self-calibration of a 2D metrology stage, based on a lattice structured artefact. The original method and subsequent later improvements have in common that the problem is solved by using some assumptions regarding the artefact used in the calibration; like that the locations of the marks in the lattice are approximately known. There are also other constrains in the mathematical solution that limits its practical use in the industry.

In this paper the application of a new general self-calibration algorithm is presented giving a large freedom to the positioning of the artefact, and also less demands on the 2D-structure on it. Rather than being based on rigorous mathematics requiring very exact positioning of the artefact, our algorithm is using a numerical iterative technique to minimize all overall errors. The algorithm is an enhancement of the self-calibration method already published by P. Ekberg et al. The algorithm has successfully been tested by simulations and by using real data from a white light interference microscope, yielding X,Y precision of few nm. The algorithm has also been used for separating distortions in ordinary low cost camera based systems opening up possibilities for accurate measurements in images. In the latter case the images can be compensated for most errors, like barrel or pin-cushion distortions, as well as perspective effects due to the angle of the camera relative the object.

Keywords: Self-calibration, White light interferometry, Image processing, Ultra precision metrology

1. Introduction

The ultimate goal in geometrical measurements is to find the true shape of the measured object. In the general case this can only be done down to an uncertainty level set by the instrument used for the measurement. Using a CMM or images retrieved from different kinds of microscopes and camera systems there will be noise and systematic deviations coming from the mechanical and/or optical systems. The traditional way to overcome this problem is to use calibrated and traceable artefacts. Provided the reference artefact is known it is in principle possible to make an absolute calibration of the measurement system by having the scale of the artefact traceably measured to the best accuracy. When aiming for ultra-precision measurements, with uncertainties in the nm-range, this calibration procedure suffers from the absolute 2D uncertainty of the traceable artefact, as obtained in an approved metrology laboratory. This uncertainty may well be larger than the new ultra precision metrology tool being developed, as it has been traceably measured in a less accurate system.

Using self-calibration is then the way to find the instrument correction function (ICF), without being dependent on neither a calibrated instrument nor a calibrated artefact, except for a 1D traceable measurement between two points on an arbitrary 2D artefact, preferably a point matrix. The result from the self-calibration gives the true shape of this point matrix artefact.

In references [1-3] the rigorous mathematics involved in the self-calibration problem is presented. In practical applications this strict mathematical solution suffers from constrains that seldom can be fulfilled. The most important being, the different measurements need to be very well aligned. To circumvent the alignment criteria we have developed a new self-calibration method built on the principles described in [4]. In this paper we demonstrate its potential by applying it on intensity images obtained by our Zygo New View 7300 white light interferometry microscope. At least three images of the lattice structured artefact are used. By running the self-calibration algorithm we can separate errors of the microscope system, like barrel or pin-cushion distortions and perspective effects, and simultaneously get the true shape of the artefact. After correction by the ICF we achieve an X,Y precision of a few nm.

2. Simulation

To illustrate the usefulness of the new algorithm and that it can handle strongly skewed image data we perform a simulation. A reference artefact (with a matrix of 10 x 9 points) is viewed by a camera. Three different image views are captured by moving and rotating the artefact as shown in figure 1, while the camera is fixed.

From these images the artefact shape and the ICF is found by iteration of the new self-calibration algorithm. The ICF is then used to correct single images distorted by the camera system, yielding much improved X,Y measurement performance.

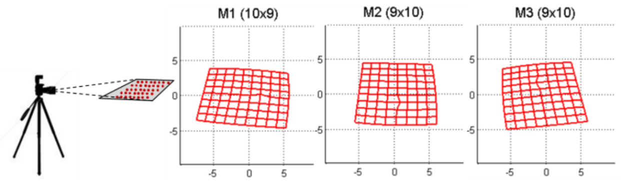

Figure 1. A camera is observing an artefact from some distance. M1 is the reference view, M2 is 90 degree view. M3 is another shifted 270 degree view.

As seen in figure 1 the images of the artefact is distorted from a perfect rectangular grid. This distortion is caused by a simulated combination of deformations and a "bump" on the artefact and a barrel distortion in the camera. For demonstration purposes the simulated errors are exaggerated. After running the self-calibration algorithm we find the true shape of the artefact with its bump and the barrel distortion in the camera as shown in figure 2.

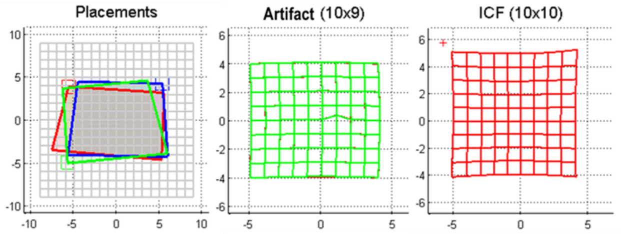

Figure 2. Left: Placements of the views as seen by the camera. Middle: The artefact shape. Right: The ICF, correcting for barrel distortion.

3. White light interferometer microscope 2D calibration

White light interferometer (WLI) microscopes are mainly used for height (Z) and surface roughness measurements. However, micro manufacturing calls for very accurate measurements in X and Y. Microscope systems often suffer from image distortions, e.g. pin-cushion or barrel distortions. Another error source that influence measurements in microscope images is the non-uniform light illumination. This therefor puts extra demands on the processing of the images. We have therefor developed a dedicated image processing algorithm for the purpose of finding feature locations in images with extremely high accuracy. This algorithm has been used to process the images in a self-calibration evaluation of our Zygo WLI. Figure 3 shows the artefact (Metrochip #1837 from Ted Pella) used for the self-calibration. One of the blob images is shown together with an example blob which centre location is calculated using advanced image processing.

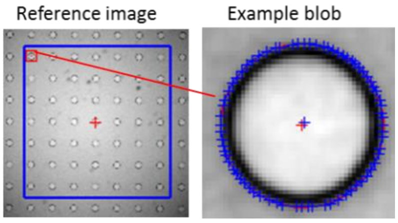

Figure 3. Left: The 25 µm pitch pattern captured at 50X. The blobs used in the self-calibration appear in the blue frame. Right: The involved pixels for the estimation of the centre of one blob (blue crosses) and the best fit circle (red) with its centre (red cross).

In the calibration we used five different views of the artefact covering a field of view of 175 x 175 µm^2 using the 50x objective. The pitch of the pattern is 25 µm. In figure 4 we show the five placements and an example of one of the results from the image processing of the Centre Of Gravity (COG) estimations.

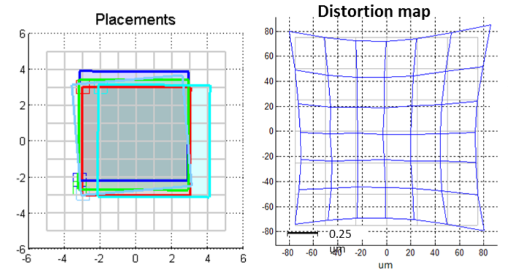

Figure 4. Left: The five placements, i.e. views used. Right: The result from the processing of the image shown in figure 3. Please note dual scales, light grey grid for the blob location, and blue crossings showing the deviations from the grey grid but at the scale given by the black bar (0.25 µm). Please note the huge distortion.

Table 1. The rotation and translations of the five measurements

Measurement	Rotation (degrees)	Shift (pitch units)
1	0	x:0 y:0
2	90	x:-0.14 y:0.84
3	90	x-0.14 y:0.36
4	95	x:-0.25 y: 0.33
5	0	x:0.99 y:0

2.2. Results

Figure 5 shows the result after self-calibration.

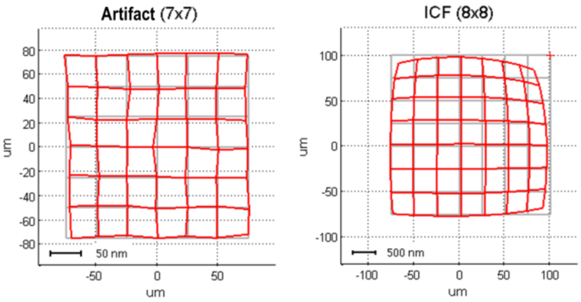

Figure 5. Left: The artefact shape. The deviation of the artefact from the perfect grid is 3.1 nm (1σ). Right: The ICF. Note the dual scales.

4. Conclusion

Without separating the errors it is not possible to get a true measurement of the artefact, as the ICF is much larger than the deviations in the artefact. The standard deviation of 3.1 nm from the theoretical grid is very good and this is in line with the specification of the artefact used (ppm accuracy in pitch). The repeatability of the images from the WLI is in the range 2-3.5 nm (1σ). So if the artefact was perfect (which of course is not the case) the result is indeed very promising.

Acknowledgement

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