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AUTOMATION OF BASIC MEASUREMENT TASKS OF THE NANOMETER COORDINATE MEASURING MACHINE

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ABSTRACT

The Nanometer - Coordinate - Measuring - Machine (NCMM) is developed for comparatively fast large area scans with high resolution. The system combines a metrological atomic force microscope (AFM) with a precise positioning system (NMM-1). The sample is moved under the probe system via the positioning system achieving a scan range of $25 \times 25 \times 5\mathrm{mm}^3$ with a resolution of $0.1\mathrm{nm}$. The automation of basic measurement tasks is critical for commercial use in nanometrology. A concept for automated measurements using a-priori-knowledge is introduced. Through the use of a-priori-knowledge measurement plans can be created offline. Dimensional markup language (DML) is used as a transfer and target format for a-priori-knowledge, measurement plans and measurement data. Using image registration in combination with an optical microscope, regions of interest and markers can be identified automatically. After the optical measurement of the part coordinate system the measurement of the measurement elements with the AFM sensor of the NCMM is done. In contrast to commercial AFMs the NCMM has the possibility to do measurements in non-raster-patterns and to do real coordinate measurements. In two case studies the use of the automated measurement is shown. In the first case study the calibration of the device using VDI/VDE guideline 2656 is automated. In a second case study the characterization of a commercial nanofiltration membrane is done for the purpose of quality assurance.

Index Terms— nano measuring machine, atomic force microscope, iterative closest point (ICP), automation, a-priori-knowledge, measurement planning, Dimensional Markup Language

1. INTRODUCTION

Atomic force microscopes (AFM) are important tools in science. AFMs suffer from some problems resulting from the measurement principle. The common measurement strategy of AFMs is called grid scans. The measurement area is measured by parallel line scans. This strategy is very time consuming, because of the serial kind of data aquisition. Proper calibration and highly skilled personnel is needed to get good measurement results. According to AFM manufacturers only 50% of the AFM users calibrate their AFM measurement devices. This leads to relative measurement errors up to 20%. This paper adresses both problem categories by introducing methods for the automation of AFM measurements. In the first part a concept for automated AFM measurements using a-priori-knowledge is reviewed. In the second part the use of image registration for the purpose of optical search of regions of interest and marker structures is reviewed and improvements by the use of the iterative closest point (ICP) method are presented. In the third part the framework is used for the calibration of our measurement setup using VDI/VDE guideline 2656 and the characterization of a commerical nanofiltration membrane.

2. A CONCEPT FOR AUTOMATED AFM MEASUREMENTS USING A-PRIORI-KNOWLEDGE

The serial measurement principle of the AFM imposes huge limitations to the maximum measurement speed. Therefore it is recommended to reduce the measurement area to a minimum. Due to the relative low positioning repeatability and the small measurement range of common commerical AFMs it is difficult to adress surface features exactly. Most AFMs are equipped with an optical microscope for a manual alignment of the AFM cantilever over the region of interest. These limitations can be eliminated by the use of long range AFM profilers with interferometric length measurement, like the NCMM, and a-priori-knowledge. The concept involves the following steps (see figure 1). The first step is the generation of a-priori-knowledge. A-priori-knowledge is all information, which is gathered independent and before the AFM measurement. In

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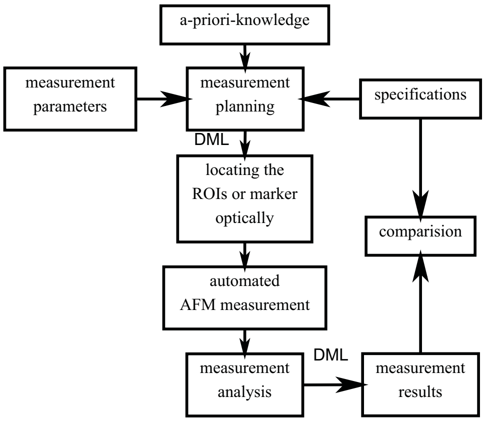

Fig. 1. Concept for automated AFM measurements

this paper the a-priori-knowledge is generated by measurement with the optical measurement microscope of the NCMM. Nearly the complete functionality of an optical coordinate measuring machine is implemented into the control software of the NCMM. The raw measurement data from the optical microscope is pre-processed. The measurement elements, markers and orientation points are extracted. This data is combined with measurement parameters and specifications in a measurement plan. The measurement plan is saved in Dimensional Markup Language (DML). After that the control software of the NCMM reads the measurement plan. The marker structures are automatically identified by image registration. After the estimation of the orientation and the position of the sample the AFM measurement is executed automatically. Measurement results are saved in DML for further analysis.

3. LOCATING REGIONS OF INTEREST USING DIGITAL IMAGE PROCESSING

The image registration algorithms involve two steps, segmentation/clustering and the actual image registration. The segmentation separates the image objects from the background. In our past works three algorithms were tested for this task. The first algorithm is based on an canny edge detector combined with a morphological operation. The second algorithms is based on watershed transformation. The third one is based on a level set method. Marker structure can be categorized in two classes, closed and open marker structures. Closed markers have a closed boundary (see figure 4). Open marker structures are composed of a cloud of smaller objects (see figure 2a). For the segmentation of open marker structures a separated clustering step is needed to recognize the whole marker object. In our earlier works one algorithm based on Fourier-Mellin-Transform was used to do the image registration task. The basic task of an image registration algorithm is to determine the transformation model between two images. In this work a second image registration algorithm is introduced. The ICP is the "‘Golden Standard"’ in image registration of medical images. The algorithm is also used for image registration tasks in combination with point cloud data from laser scanners. In this paper a slightly modified version of an algorithm called LM-ICP is used[1]. In our case the model class is affine. Translation in the lateral axes, x and y, and also rotation around the z axis is allowed. The implemented algorithm is a feature-based image registration algorithm. In our implementation the features are edge points extracted with a Harris Corner detector[2]. The extracted point clouds of the two images to register converge to a final overlapping optimization results based on the least square distance measure and a nonlinear solver, the Levenberg-Marquardt algorithm[3]. The optimization result of the original algorithm depends on the start conditions. The modified version uses the principal component analysis[4] to determine a set of good start parameters and solves this problem.

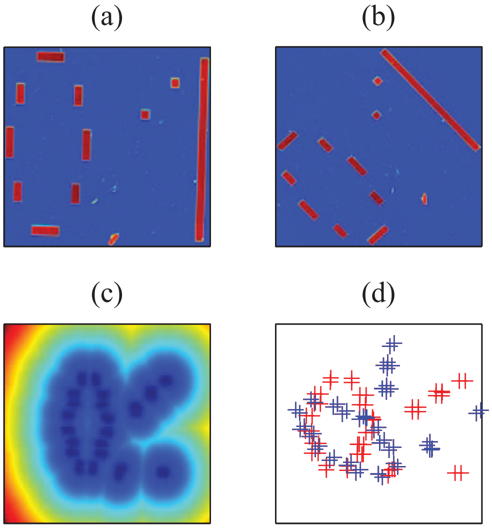

Fig. 2. Image registration using ICP: (a) marker; (b) rotated version of (a); (c) distance transform of the Harris corner points of (a) used to estimate the model error; (d) extracted Harris corner points of (a) and (b)

4. CASE STUDIES

In this section the measurement concept is applied to two problems in nanometrology, the calibration of our AFM based on VDI/VDE guideline 2656 and characterization of commercial nanomfiltration membranes.

4.1. Calibration based on VDI/VDE guideline 2656

The calibration of AFMs is a time consuming and complex task. There is a need for automation of this

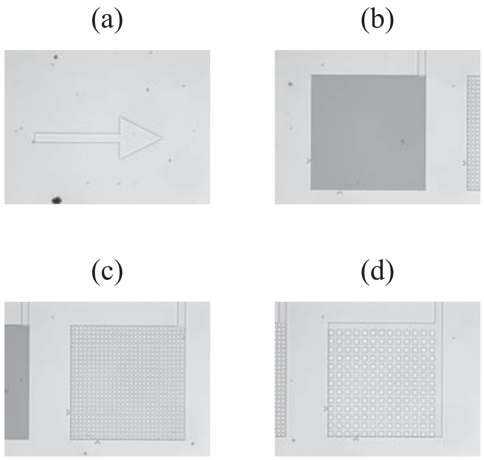

Fig. 3. Lateral Calibration Standard VLSI STS3-1800P (a) marker structure (b-d) calibration area

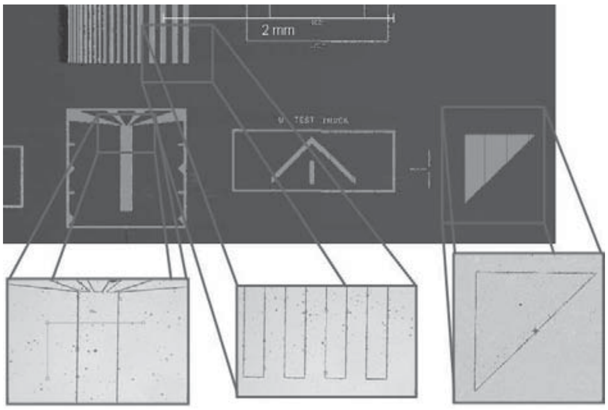

Fig. 4. VLSI step height sample with markers(triangle) and measurement areas(step height/ grid pattern)

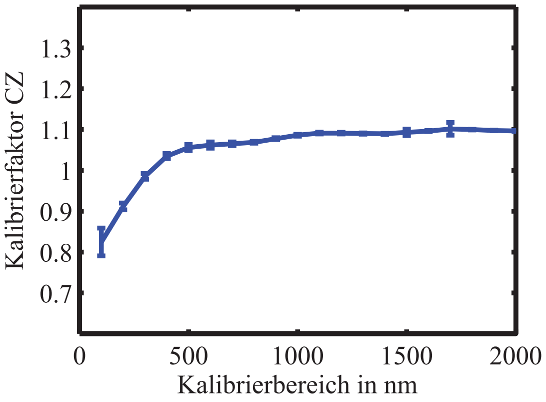

Fig. 5. Nonlinearity of the strain gauge of the AFM

task in the everyday lab routine. At first one has to differentiate between one-time and frequent calibration tasks. A one-time calibration task is for example the pre-calibration of an AFM. This task includes the characteriziation of the drift, noise and guidance behaviour of the device. The pre-calibration should be progressed at the beginning of operation of a device and after changes to the measurement setup. A frequent calibration task is for example the calibration of the metrological sensor of the AFM. The time interval for frequent calibration depends on the metrological category and the long time stability of the measurement device. Depending on the calibration interval automation is more or less resonable. For our setup the calibration interval of the z-axis should be daily and the calibration interval for the lateral axes should be monthly. For the calibration of the lateral axes the VLSI standard STS3-1800P is used. The standard has four calibration areas with waffle-like structures and different pitch values. There are also marker structures to guide the user to the calibration areas. Using image processing the marker structure (see figure 3a) can easily be detected and used as part coordinate system for the calibration task. The calibration of the z-axis can be implemented in a similiar way (see figure 4). The calibration of the nonlinearity of the z-axis with a set of VLSI step height standards with different heights can not be automated in this way, because for the calibration procedure a manual exchange of the different standards is needed. This procedure is substituted by the following procedure. The laser interferometer of the z axis can be use for calibration. This is the common technique for the calibration of a measurement sensor on the nano measuring machine. To do this calibration ramp profiles are use to move the measurement sensor through its measurement range. After that the calibration factor is evaluated by linear regression between measurement data of the interferometer and the measurement data of the sensor to calibrate. This method has some drawbacks. The measurement data is distorted by control errors. The distortions can not be separated from the data. The number of observations is low. Very small measurement ranges can not be calibrated. Our method uses ”step height”-like profiles for the calibration of the metrological sensor of the AFM. The measurement data is evaluated by the ISO 5436 - method. With this strategy the distorted regions of the measurement data can be separated and it is possible to calibrate the nonlinearity of the metrological sensor of the AFM in arbitrary steps and arbitrary ranges (see figure 5).

4.2. Characteriziation of a nanofiltration membrane

The nanofiltration membrane chip has a chessboard-like structure with numbers and letters to adress every membran area. The membran areas are structured

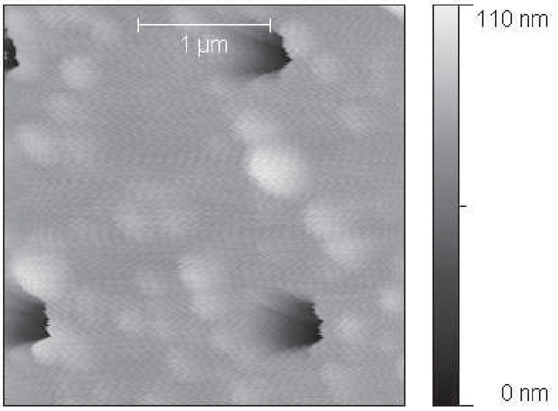

Fig. 6. AFM measurement of a nano pore (size: $3 \times 3\mu\mathrm{m}$ / resolution: $8\mathrm{nm}$)

with nanopores of a diameter of about $350\mathrm{nm}$. The nanopores are ordered in a rectangular grid structures with a pitch of $2\mu\mathrm{m}$ in both dimensions. Every membrane area has 48116 nanopores covering an area of $100 \times 2100\mu\mathrm{m}^2$. The full characteriziation of the pores fails with common measurement techniques. The pores are to small for optical measurement techniques like optical microscopy or white light interferometry. For the use of scanning electron microscopy the samples have to be coated with a small layer of metal, which changes the sample. Scanning electron microscopy is not traceable to the meter dimension and has a low measurement range. Common AFMs only have a small measurement range of about $150 \times 150\mu\mathrm{m}$ and a low positioning repeatability. The only option is a metrological longe range AFM, like the NCMM. Previous works show problems with the tip wear and also orientation on the sample. The idea to solve the problems of tip wear was to measure a random sample of single pores instead of measuring the whole surface. The chessboard-like marker structure makes it possible to adress the different membrane areas automatically by image registration. The nanopores are not optical visible as single features, but as a change in the surface texture. It is therefore not possible to adress and measure single pores directly with optical guidance. The first measurement strategy is to measure the outer edge of the membrane area by the AFM to estimate the grid orientation and position. This can easily be done by the application of a threshold criterion and the use of the center of gravity method on the measurement data to estimate the center coordinates of the pores. The orientation or rather the principal axes of the resulting point cloud are estimated by principal component analysis. Practical measurements show that it was not possible to adress single pores due to drift effects and tip wear. The second strategy is to measure whole columns or rows of nanopores with a safety range. This strategy is regarding view to tip wear not superior to grid scans, but it is possible to adress single rows or columns. The last and final method is to measure a sample population of nanopores through the measurement of random patches in the membrane area, followed by the extraction of the nanopores post-processing.

5. CONCLUSIONS AND OUTLOOK

This paper reviews a concept for automated AFM measurements using optical guidance, image processing and a-priori-knowledge. The image registration routines were improved by the use of an ICP algorithm. The framework was applied to calibration and measurement tasks. A new method for the calibration of measurement sensors was proposed. Different measurement strategies for the measurement of nanofiltraion membranes were evaluated. The measurement and evaluation of nanopores still shows open problems. In future the performance of wear resistant, diamond-coated cantilever tips will be evaluated. Also measurement strategies with online signal processing and feature-dependent sampling rates will be evaluated. Signal processing methods for the extraction of the geometric parameters of nanopores from the measurement data have to be developed.

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