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Entwicklung eines 3-D-fähigen Antastsystems auf Basis elektrischer Nahfeldwechselwirkungen für die Mikro- und Nanokoordinatenmesstechnik

Development of a 3D capable probing system based on electrical near-field interactions for micro- and nano-coordinate metrology

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Kurzfassung

Die messtechnische Erfassung von Bauteilen der Mikrosystemtechnik und von Komponenten mit Mikrostrukturen stellt die Mikro- und Nanomesstechnik durch stetig kleiner werdende Strukturgrößen und steigende Aspektverhältnisse der Strukturen vor große Herausforderungen. Hierfür sind nanometerauflösende, 3-D-fähige Messverfahren sowie entsprechende 3-D-Positioniersysteme und Antastsensoren erforderlich. An der Friedrich-Alexander-Universität Erlangen-Nürnberg wird ein mechanisch-berührungsloses, subnanometerauflösendes 3-D-Mikrotastsystem auf Basis elektrischer Nahfeldwechselwirkungen entwickelt und untersucht. Das System wird als Tastsystem einer Nanopositionier- und Nanomessmaschine NMM-1 eingesetzt. Zur Erhöhung der Messdynamik und Erweiterung der Einsatzmöglichkeiten wurde das Tastsystem um einen piezoelektrischen 3-D-Nanopositionierer und eine 3-D-Antastvektorermittlung aus dem Sensorsignal erweitert.

Abstract

With decreasing structure dimensions and rising aspect ratios of the products the demands for micro- and nano-metrology to measure the components of microsystems and components with microstructure have increased. Therefore nanometre resolving 3D capable probing sensors and corresponding 3D positioning systems are required. At the Friedrich-Alexander-Universität Erlangen-Nürnberg a mechanical contact-free, sub-nanometre-resolving 3D micro probing system based on electrical near-field interactions has been developed and investigated. This system is as a probing system integrated in the nanopositioning and nanomeasuring machine NMM-1. To improve the measuring dynamics and expand the application possibilities the probing system has been extended with a 3D movable piezoelectric nanoscanner to directly detect its probing direction from the measurement signals.

Keywords: probing system, micro CMM, nano CMM, scanning tunnelling microscopy (STM)

Introduction

Driven by current micromanufacturing technologies the market of micro components and micro products undergoes an increasing advancement. The major product groups are mechanical and optical micro parts as well as bio-medical devices. Furthermore micro-electro-mechanical systems (MEMS) with three-dimensional structures are becoming increasingly important for industrial applications and consumer products. Therefore, nanometre-resolving 3D capable sensors and 3D positioning systems to operate the sensors to measure three dimensional nano-/micro-geometries over a large area are demanded. Special micro- and nano-coordinate measuring machines with resolution in the nanometre and sub-nanometre range are already available for measurements over relatively large ranges of several millimetres. But there is still an open requirement for the nanometre-resolving probing sensors. Nowadays several sensor measurement principles are available for micro- and nanometrology. However, optical probing systems are limited in measurement of samples with high aspect-ratios. Microtactile

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sensors have limitations in the structural resolution, measurement speed and stylus stiffness. To overcome these limitations a probing system based on electrical nearfield interactions has been developed at the Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU). By using the nanopositioning and nanomeasuring machine NMM-1 to operate the sensor nanometre resolved surface topography measurements as well as 3D micro coordinate measurements are feasible.

Development of a 3D electrical near-field probing system

This mechanical contact-free work piece probing is derived from the principle of scanning tunnelling microscopes (STM). Fig. 1 shows the general setup of the heart of this electrical probing system by utilizing a metallic sphere with a diameter on the order of 0.1 mm as a sensor electrode. By applying a bias voltage U between a conductive work piece and a conductive probe, a tunnelling current I_T of a few nanoamperes can be detected if both electrodes are brought within a sufficiently small distance s. The occurring tunnelling current increases exponentially with a decreasing distance between the two electrodes. As a result of the extension of the electrical interaction area between the two electrodes the practically applicable range of working distance will be increased up to 200 nm [1]. A precise current amplifier with variable amplification factors can be used to amplify and convert the tiny current signal (in nA range) into a voltage U_T (limited to ±10 V).

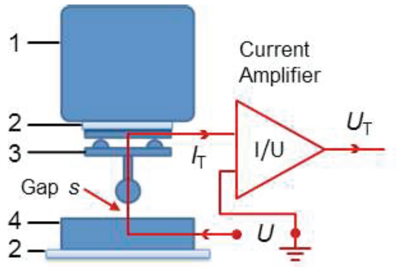

Fig. 1: General setup (1) probe holder; 2) electrical insulator; 3) exchangeable probe with metallic probing sphere; 4) electrically conductive work piece; I_T: tunnelling current; U_T: amplified sensor signal; U: bias voltage).

The investigated probing system was integrated in NMM-1 to increase the sensor's measurement range. Differing from the conventional coordinate measuring machines (CMM) the NMM-1 moves not the probe but the sample, which is placed on a moveable corner mirror. With the help of a three-axis drive system a movement within a range of 25 mm x 25 mm x 5 mm is possible. The displacement of the corner mirror is measured by three fixed laser interferometers, whose measurement axes intersect at a single point. This arrangement makes the positioning system fulfil the Abbe principle in all three coordinate axes. Hence a positional resolution of less than 0.1 nm and positioning uncertainty less than 10 nm over the entire measurement range can be achieved [2]. The interferometer signals and the sensor signals from the integrated probing systems are processed synchronously by the electronic unit of the NMM-1. Thus the drive system and the measuring procedure can be controlled. After that a new 3D control system based on the I++ DME (Inspection plus-plus for Dimensional Measurement Equipment) specification was implemented in the NMM-1 firmware, the demands of scanning probe microscopy (SPM) and micro coordinate measurements to carry out complex 3D measurement tasks are also fulfilled [3].

For topography measurements with the combination of the electrical probing system and NMM-1 the voltage signal from the current amplifier can be used as the input for the NMM-1's position control of the *z*-axis. During the lateral scan the stage moves in addition in vertical direction to follow the surface in order to keep the voltage at a constant value. In this case, the *z*-interferometer values from the NMM-1 represent the height deviations of the specimen [4].

As any part of the spherical stylus tip (except for the part joined with the stylus shaft) can be used for electrical probing of specimen and behaves isotropic, this sensor is possible to apply for the tasks of 3D coordinate measurement [5]. By using the single point measurement instruction of NMM-1 with a predefined surface normal vector the form deviations of the work pieces can be calculated from the sensor distance signal in the probing direction and the interferometer values from the NMM-1.

A rotary kinematic chain was also developed and tested for this electrical sensor to increase the effectively measurable surface angle and to reduce measurement deviation by keeping the sensor in its optimal working angle during the measurement [6].

Within an ongoing research project the electrical near-field sensor is being updated to a probing system with real 3D capability and applied as an active probing system [7]. Differing from the force signal of a tactile probe, the electrical signal is only a scalar, and the direction information has to be gathered in addition.

In the current setup a 3D movable piezoelectric scanner (resonance frequency > 1 kHz for all the three axes) with a precise motion range of 10 µm x 10 µm x5 µm along the *x*-, *y*- and *z*-axis is utilized to oscillate the probe (see Fig. 2). The actuator with integrated capacitive sensor is driven by a DSP-based (Digital Signal Processor) servo controller. User-generated positioning commands can be supplied via the analogue BNC inputs, the USB or parallel interface, amplified by the ultra-low-noise drive amplifier and then applied to the actuator. As sine and cosine wave signals are synchronously applied to the actuators, the probe moves on a circular path of some nanometres and, as a result, a sine-wave-like periodic sensor distance signal will be measured. The probing direction can be derived from the relation between sensor signal and circular sensor positions, cf. [8]. The algorithms to determine the probing direction will be described in detail in the next section.

Fig. 2. Updated electrical near-field probing system installed in NMM-1

By using the scan measurement instructions of NMM-1, the ability of the sensor system to follow a surface contour depends not only on the applicable working range of the sensor but also on the control dynamics of the NMM-1. Since the working range of the electrical sensor is limited to a maximum of 200 nm (by using a metallic sphere with a diameter of 0.3 mm as a probing tip), the electrical interaction requires a highly accurate tracking of the positioning system to maintain a constant distance. Therefore the NMM-1 has to allow a very fast response and a large adjusting movement. But due to the high mass of the corner mirror and possibly also heavy samples the control dynamics of the NMM-1 is restricted. So the used piezoelectric actuator, which carries comparatively much lower masse (< 15 g), is intended to provide additionally a faster response for the rapid motion. In this case both the sample and the probe are moveable in all three axes and their positions are registered synchronously during the scan measurement. The updated electrical probing system acts thus as an active probing system and not as zero-indicator as before. The contour of the specimen is calculated from distance signal of the current sensor, the position values from capacitive sensors integrated the in piezoelectric actuator and the interferometer values from the NMM-1.

An active probe controller (APC) based on a DSP-board with eight ADCs and DACs (with several backups) has been designed for signal processing (see Fig. 3). The signals of the piezo actuator position and the amplified sensor signal are registered by the analogue input channels. The analogue output channels are used to supply the piezo control input signals.

The DSP unit acts as a trajectory generator for the harmonious movement of the 3D actuator and calculates the probing vector from the synchronously registered sensor signal and piezo position signals. For the operation as an active probing system the DSP also realizes the active probing control in the probing direction. The developed DSP unit must be synchronized with the position control unit of the NMM-1. The DSP can be controlled and configured via a USB connection by an operating computer.

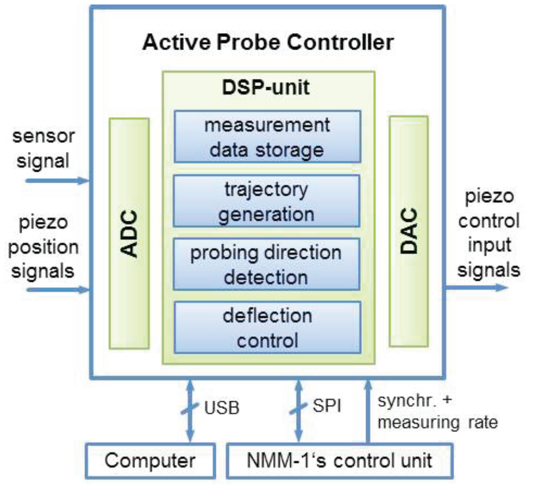

Fig. 3. Bock diagram of the control electronic for the electrical sensor

Algorithms to determine the probing direction

Fig. 4 shows as an example a side wall probing of a gauge block with the updated sensor system. The oscillation movement in x-y-plane can be carried out completely inside the reliable sensor working range or partly outside with a bigger movement path.

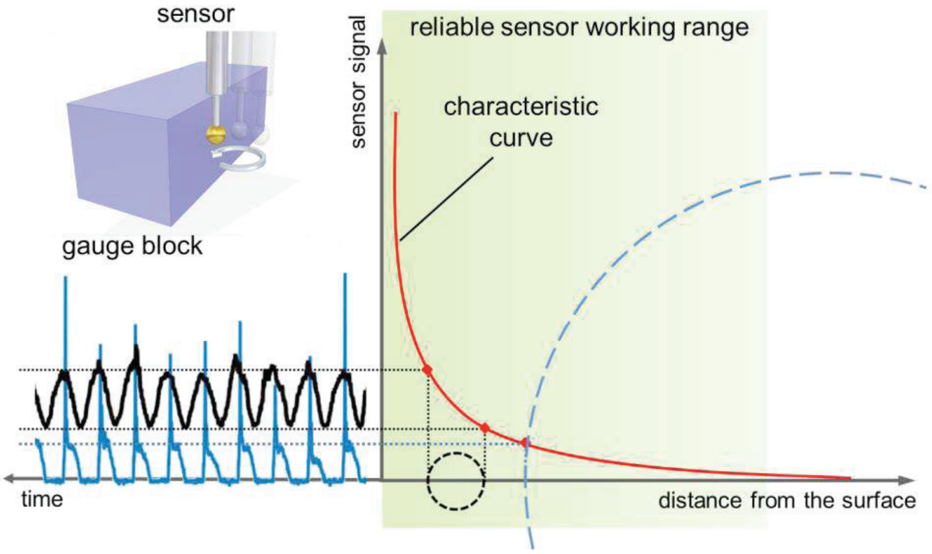

Fig. 4. Performing a circular movement of a spherical tip in the near of the side wall of a gauge block

When the whole trajectory is within the working range, a sine-wave-like periodic current signal (the black signal in the figure) will be measured. In the other case intermittent signals (the blue signal in the figure) with bigger interruptions and noises are observed. And the signal behaves also asymmetrically. It is caused by the drifts and vibration effects of the piezoelectric actuator and also the mechanical nearfield interactions.

The in Fig. 5 specified angle ϕ in the piezo actuator coordinate system, consequently the resulting vector ($\cos\phi$, $\sin\phi$), presents the probing direction. Depending on the accuracy of the mechanical adjustment of the sensor system the coordinate system of the NMM-1 is parallel to that of the actuator, but rotated (180° about the x-axis and 90° about the z-axis). So a coordinate rotation with the rotation matrix R_m in equation (1) is here necessary to calculate the probing vector in the coordinate system of the NMM-1.

$$\begin{bmatrix}x\\y\\z\end{bmatrix}_{NMM-1} = \boldsymbol{R}_m \begin{bmatrix}x\\y\\z\end{bmatrix}_{Piezo} \qquad (1)$$

with $\boldsymbol{R}_m = \begin{bmatrix}0 & -1 & 0\\ -1 & 0 & 0\\ 0 & 0 & -1\end{bmatrix}$

The sensor signal and the x- and y-position signals of the piezoelectric actuator registered by APC are plotted in Fig. 6. With an oscillation frequency of 20 Hz the probe moved on a circular path with a diameter of 0.14 µm in the x-y-plane within the working range of the electrical sensor.

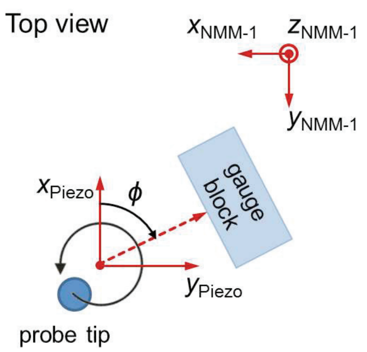

Fig. 5. Arrangement of the coordinate system of the piezoelectric actuator and NMM-1 (ϕ: angle to be determined)

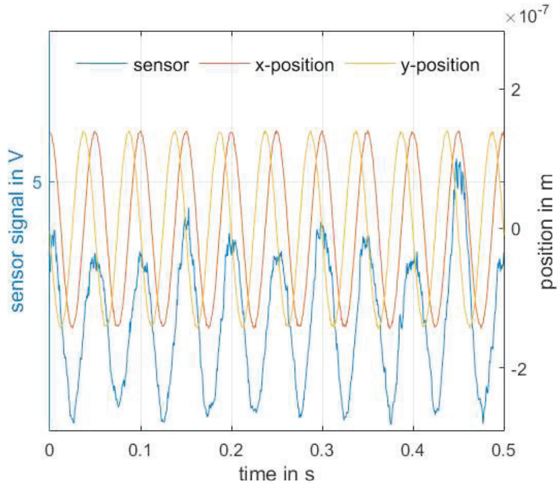

Fig. 6: Measurement results of repetitive probing on a gauge block via oscillation of the probing sphere

Within a period of rotation the maximal current signal will be detected when the probe stands nearest to the surface. With the help of the corresponding *x*- and *y*-coordinate the specified angle ϕ can be identified in the piezo actuator coordinate system. Because of the noise and vibration effects some runaway values appear just before or after the deserved maximum. Thus the calculated angle in each period varies significantly for a simple search for the maximum. Therefore, an area moment method [9] can be used to detect the centre point of an area within a probing period in the time axis. With the help of a threshold line in Fig. 7 periodic segment areas A_i enclosed by the sensor signal $f(t)$ and threshold line can be built up. The centre of the area in the time-axis ($t_{i,c}$ between $t_{i,b}$ and $t_{i,e}$) can be calculated from the equation (2).

$$t_{i,c} = \frac{\sum_{i,b}^{i,e} f(t_i) \cdot t_i}{\sum_{i,b}^{i,e} f(t_i)} \qquad (2)$$

The *x*- and *y*-coordinate at this moment $t_{i,c}$ is used to calculated the corresponding angle ϕ as for the maximum-searching method.

As the recorded sensor signal performs sine-like, the best-fit method for sine function can also be used to analyse the characteristics of the signals. The frequency is defined by the circular movement, therefore only the amplitude and the phase shift should be calculated. The difference between the phase shifts of fitted curve of the *x*-position signal and the sensor signal is consistent with the angle ϕ. The general used method of Fourier analysis provides another way to directly determine the phase shift. The signals can be converted into the frequency domain. The phase lag, which corresponds to the defined oscillation frequency, is to be calculated for the two signals.

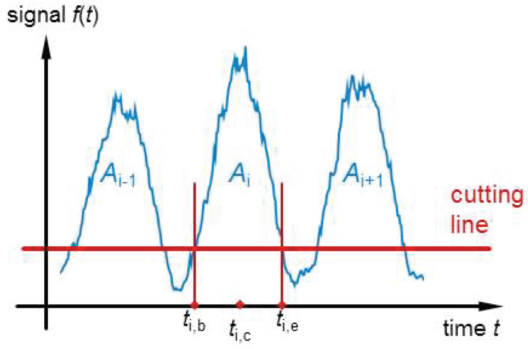

Fig. 7. Determine the centre point of time for each period with the area moment method

The signals plotted in Fig. 6 were used to calculate the angle ϕ specified in Fig. 5, see Tab. 1. The determined angles with area moment method (-10.9427°) and Fourier analysis (11.0169°) are highly agreed. The results determined with the first two methods exhibit a standard deviation of about 13.6°. It indicates that the calculated angles for each period spread out over a wide range of values. As the sensor signal behaves not the same for each period, a sufficient number of periods are necessary for these two methods in order to get a reliable average value. But it will certainly cause a time exposure. The best-fit method, because of the iteration procedures, is comparatively more time-consuming. So it is preferred to implement Fourier analysis in the DSP unit for calculating the probing direction.

Tab. 1. Calculated results of the angle ϕ for probing on a gauge block with different analysis methods

Analysis method	angle ϕ	
Maximum-search	-6.6135° (average)	13.6229° (st. dev.)
Area moment	-10.9427° (average)	13.6186° (st. dev.)
Sinus fit	-8.0214°	-
Fourier analysis	-11.0169°	-

To compare the different evaluation algorithms to determine the probing vector described in the last section some other measurements were also done. As an example, the probing with a spherical probing element (diameter 0.3 mm) on a metallic calibration sphere with a diameter of 2 mm is shown in Fig. 8. The oscillation was carried out in the *x*-*z*-plane in the actuator's coordinate system. At the illustrated position in Fig. 8, the desired value of the angle should be about 60°. As shown in Tab. 2, the results of the last three methods are more agreed.

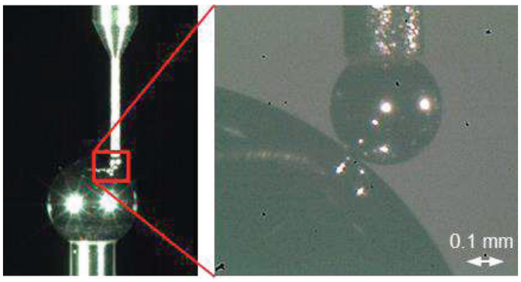

Fig. 8. Probing on a calibration sphere (left, carbide, diameter 2 mm) with a spherical probing element (right, carbide, diameter 0.3 mm)

Tab. 2. Calculated results of the angle ϕ for probing on a calibration sphere with different analysis methods

Analysis method	angle ϕ	
Maximum-search	54.9592° (average)	8.3792° (st. dev.)
Area moment	60.3487° (average)	4.7512° (st. dev.)
Sinus fit	60.8197°	-
Fourier analysis	61.1894°	-

The measurement uncertainty of this electrical probing system can be influenced by several factors. A major contribution to the measurement uncertainty is the effect of form deviation and the roughness of the tip. Thus high precise spherical stylus tips must be used and the form deviations need to be calibrated and compensated. Besides the sphere itself the contaminations have also a significant impact on the measurement result. It is necessary to pay more attention to careful cleaning of the work pieces and the stylus tip ball. Another problem is the limited accuracy of the piezoelectric actuator and the integrated capacitive sensors, which leads to an incorrect circular movements or an inaccurate reading of the current positions. The measurement uncertainty is also limited by the characteristics of the electronic components, especially the noises and time delay, which should also be modified, quantified and compensated.

Conclusion and outlook

A probing system based on electrical near-field interactions has been extended with a 3D movable precise piezoelectric scanner and an active probe controller to detect the probing direction. The setup was integrated into the nanopositioning and nanomeasuring machine NMM-1 on the mechanical and electrical levels. Different evaluation methods to calculate the probing vector have been demonstrated and verified with measurement tasks. With the superimposed circular modulation the measurement uncertainty of the probing system must be influenced comparing to the previous system for probing in a predefined direction. The metrological properties of the updated sensor system are planned to be identified within the project.

Acknowledgement

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