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A NOVEL PSEUDO-TACTILE 3D ZERO INDICATING PROBE FOR NANOMETROLOGY

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Abstract: *Today several coordinate measuring machines for the measurement of microparts have been developed, some of them are commercially available already. State of the art are axes resolutions of a few nanometers at a measuring volume of a few* cm^3*, what can be achieved by laser interferometry or scale based length measuring systems. However, the most critical part of a conventional CMM, the usually tactile probing system, is difficult to be scaled down for the measurement of microparts. Due to the small contact area between a micro tip ball of e.g. 0.1 mm diameter and a workpiece, Hertzian stress can get significant even at very low static contact forces. Depending on approach velocity and moving mass of the probing system, dynamic reactions during deceleration of the probing element upon contact may exceed the yield stress of the probed component and cause damages. When using very small probing elements this can only be avoided by drastically reducing static and dynamic probing forces.*
To achieve this, a novel 3D probing system (patent pending) was designed, which detects and measures vicinity to the work piece surface without actually touching it by the means of tunneling current measurement. Therefore a highly stabilized bias voltage is applied between a conductive work piece and a special probing element that leads to a weak, but measurable current flow if the separation between these electrodes is in the order of a few nanometers. Due to the exponential dependence of the tunneling current from separation, a radial resolution far below 1 nm could be achieved. The system has been set-up, integrated into a long range nano positioning system and tested. It is capable of conventional 2.5D STM measurements with a maximum measuring range of 25 mm x 25 mm x 5 mm, but also coordinate measurements of true 3D geometry.
Keywords: *micro/nano-metrology, scanning tunneling microscopy, coordinate metrology, micro probing system*

1. INTRODUCTION

Virtually all probing systems for coordinate measuring machines detect the workpiece surface by touching it with a probing element and measuring the contact force or the displacement of the probing element for contact detection, Weckenmann (2005). When the size of the probing element is reduced for the benefit of better accessibility to small interior features, higher spatial resolution and lower moment of inertia, several challenges directly arise from the tactile working principle. Hertzian stress in the contact area grows quickly with smaller tip balls, (1), leading to the danger of plastic deformation of the workpiece and thus destructive testing and large measurement errors, van Vliet (1996). As the stem diameter has to be smaller, than the tip ball diameter, also stylus bending may get critical and lead to deteriorated signal to noise ratio when small tip balls are used.

$$|\sigma_{max}| = \frac{1}{\pi}\left(\frac{1{,}5 \cdot F \cdot E^2}{r^2(1-\upsilon^2)^2}\right)^{1/3} \qquad (1)$$

Equation 1: Hertzian stress while probing a plane with a spherical probing element.
σ_{max}: maximum stress in the contact area
F: probing force r: tip ball radius
υ: Poisson´s ratio
E: effective Young´s modulus

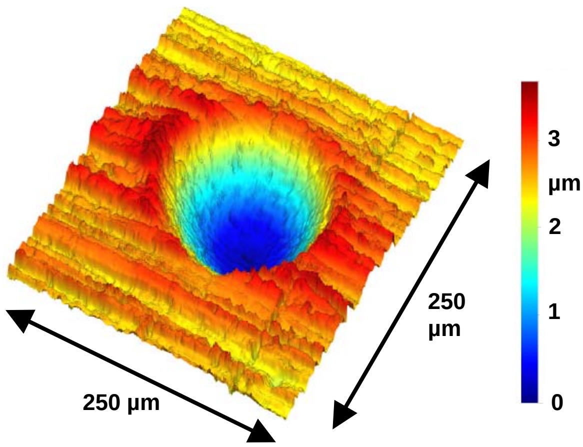

Fig. 1. Impression of a 1.5 mm tip ball in aluminum.

Fig. 1 shows the impression of a tip ball of 1.5 mm diameter after probing an aluminum surface at a probing force of 200 mN.
To limit Hertzian stress in the contact area and to avoid damages of the workpiece, static and dynamic probing forces have to be very small when using small tip balls, what leads to a demand for a very soft suspension of the probe (static forces) and very low moment of inertia of the moving part of the probing system (dynamic forces). Commercially available micro probing systems, fig. 2, face that challenge by applying micro machined and thus very expensive and also very delicate suspensions and /

or drastically reducing the probing speed, Weckenmann (2005).

Fig. 2. Commercial tactile microprobes (source: IBS Precision Engineering, Netherlands)

Another challenge for miniaturization is manufacture of mechanically stable micro stylii and their mechanically stiff connection with the suspension of the probing system. Today the smallest stylii used for tactile micro probing systems have a tip diameter of 0.2 mm. The adhesive bond used between stylus and suspension makes exchange of the stylus impossible without changing the expensive suspension.

These drawbacks, inevitably connected with tactile probing, can only be overcome by applying a measurement principle, which is independent of mechanical interaction between the probing system and the workpiece.

Optical probing systems are common for 2.5D surface metrology, but have limited lateral resolution (Rayleigh limit) and are limited with respect to 3D measurements due to a lack of accessibility to steep walls and undercuts, Weckenmann (2005).

This applies also to various techniques of scanning probe microscopy, but there is the possibility of modifying the form of the probe to enable true 3D measurements. For example assembled AFM probes, Danzebrink (2006), may be used for the measurement of steep walls, but this in turn limits accessibility in vertical direction, requires extensive manufacturing efforts and results in very fragile systems, what limits practical applicability.

A novel probing system based on electrical interaction without mechanical contact between probe and workpiece surface has been developed in order to cope with these challenges.

When using a force less electrical interaction between probing system and workpiece, the need for suspensions with a very low spring rate, a mechanically stable stylus or optical accessibility to the probe or the workpiece are obsolete, so the design of the probe can be much better optimized towards robustness, flexibility and 3D capability.

2. SYSTEM SET-UP

The measuring system, fig. 3, used for this work is set-up out of the following components:

- commercial 3D nanopositioning unit SIOS NMM-1: travel 25 mm x 25 mm x 5 mm, resolution 0.1 nm
- custom made passive probing system based on tunneling current measurement
- pneumatic vibration isolation system
- control electronics
- computer with control and evaluation software

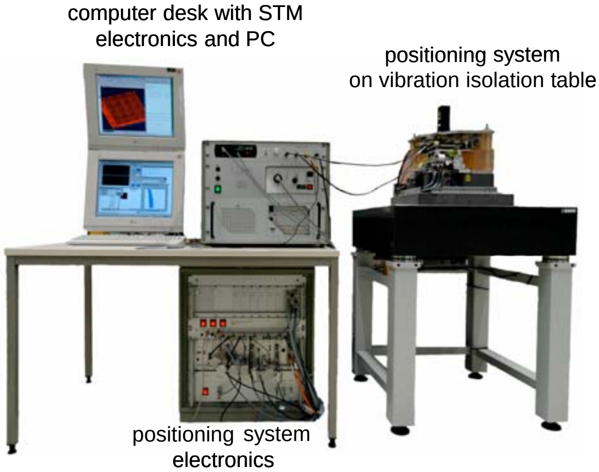

Fig. 3. Laboratory set-up of the complete system.

2.1 Probing System

The demands for force less surface detection with a lateral and vertical resolution in the nanometer order, accessibility to interior features far below 1 mm and enhanced robustness compared to tactile micro probes could be served by applying tunneling current measurement, known from scanning tunneling microscopes, for detection of the workpiece surface.

The basic principle is that a conductive probe is brought closely to the surface to be detected and a voltage between 0.1 V and 2 V is applied between both. Below a certain probe-surface separation, an exponentially separation dependent current up to some nano amperes will flow from one of these electrodes to the other even if there is no actual electrical or mechanical contact. This current can be used for very sensitive proximity sensing. For analog-digital (AD) conversion and further processing, the so-called tunneling current is transformed into a voltage signal, fig. 4. By defining an appropriate threshold for the tunneling current, vicinity to the workpiece surface can be detected a few nanometers or even less before mechanical contact is established. As the surface is detected without actual contact, but at very small probe-workpiece separation this way of probing may be referred to as “pseudo-tactile detection”.

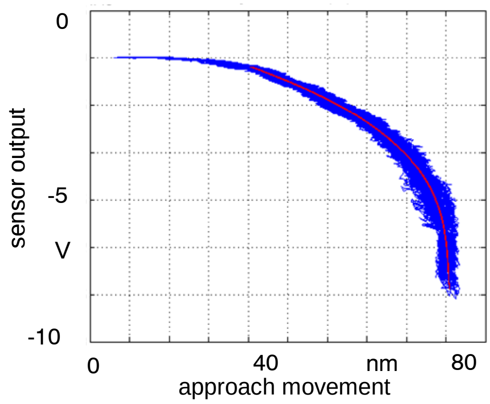

Fig. 4. Characteristic curve of the sensor when approaching to a surface.

After approaching and surface detection it possible to scan the probe along the surface in permanent interaction and to use the tunneling current for closed-loop distance control, as used in conventional STMs for 2.5 D surface metrology. In this mode the introduced system works as metrological STM with an extremely large measuring range of up to 25 mm x 25 mm x 5 mm and traceable position measurement. For very high resolution 2.5D scans with permanent probe-sample interaction and small measuring ranges, sharp needle-like probes with a curvature radius of a few ten nanometers are preferred for best resolution.

In contrast to conventional STMs it is also possible to approach to the surface, record the coordinates of the probed point and to withdraw the probe again in order to quickly move to the next probing point without interaction with the workpiece. In this mode the system works as single points measuring micro CMM. Depending on desired probing speed and accuracy, which is closely connected with the size and tolerances of the workpiece to be tested, the tunneling current signal may be just used to trigger a coordinate measurement of the positioning system (touch-trigger probing), or to evaluate it quantitatively together with the coordinates measured by the positioning system (measuring probing). In touch trigger mode a set of discrete single points is recorded and may be used for subsequent evaluation, e.g. extraction of geometric features, whereas in the measuring probing mode scanning measurements of known and unknown three-dimensional objects are feasible.

For usage with a micro CMM, probes with an isotropic characteristic are best suited, to enable for true 3D probing, so spherical probing elements with isotropic electrical characteristics are needed. For the present work monolithic hard metal probes with a probing sphere of 0.3 mm diameter and assembled and gold sputtered stylii with a 0.2 mm ruby tip ball have been used. Due to the fact that no force transmission via the stem is needed and so mechanical stability is not necessary, there is no principal limitation for the size of the stylus.

To fulfill its task of detecting a surface from various approach directions with a repeatability of a few nanometers, the probing system consists of the following main components, see also fig. 5:

- a highly stabilized tunable voltage source for creation of the bias voltage between probe and workpiece
- a current to voltage converter with selectable amplification (10^7, 10^8, 10^9) to turn the very small tunneling current into a voltage signal of 0 – 10 V for subsequent AD-conversion and evaluation
- a thermally and mechanically stable tip holder made of Invar with quick release fastener and an exchangeable probe
- an Invar grounding plate for electrically connecting the workpiece to the sensor electronics
- an oscilloscope for signal monitoring

The introduced probing system is completely passive, i.e. without any actuators or other heat sources like illumination, so it does not influence the workpiece or the metrology system thermally, Weckenmann (2006). The heat load generated by tunneling current is only a few nano watts and thus negligible.

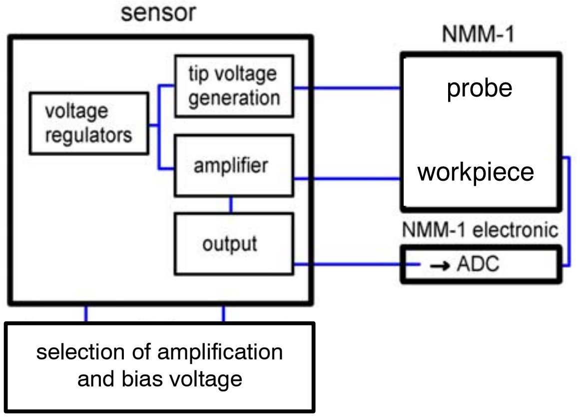

Fig. 5. Schematic system set-up.

2.2 Positioning System

To have a fully functional measuring system, besides the probing system also a positioning and position measuring system is needed. To tap the full potential of the probing system, the positioning system should have the same or better resolution, positioning uncertainty and noise level than the probing system. To enable for 3D coordinate and long range scanning measurements, the positioning system should have a range of several millimetres in each of the three axes.

For manipulating and measuring the position of the workpiece with respect to the position of the fixed probe a laser-interferometrically position controlled 3D nanopositioning and nanomeasuring machine (SIOS NMM-1), developed at the Technical University Ilmenau and manufactured by SIOS GmbH Ilmenau was chosen, Jaeger (2004).

The specimen carrier of the NMM-1 is composed of three zerodur plates, which are attached to each other perpendicularly and are mirrored on the outer faces. These mirrors serve as the moving mirrors of three homodyne HeNe-Laser interferometers that are arranged in a way that the virtual point of intersection of the beams coincides with the nominal probing point of the system, fig. 6. With this set-up first order Abbe-errors can be avoided and traceable position measurement can be carried out. Depending on the kind of probe the nominal probing point is the apex of the needle-like probe, or the centre of the probing sphere.

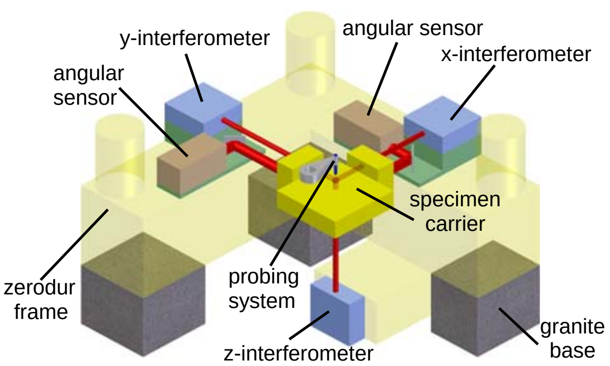

Fig. 6. Abbe error free set-up of the SIOS NMM-1.

For further reduction of geometrical errors, the angular position of the specimen carrier is monitored in three axes and closed-loop controlled in two axes. For achieving best possible thermal stability, all position and angle measuring systems are attached to a rigid metrology frame made from zerodur. Directly attached to this zerodur frame is an Invar cross-head carrying the probing system. The influence of air temperature, moisture and pressure upon the laser wavelength is compensated for.
The developer claims a volumetric positioning uncertainty of less than 10 nm (k=1) in a volume of 25 mm x 25 mm x 5 mm at a resolution of 0.1 nm. However, due to acoustic disturbances from the air conditioning in the laboratory, positional noise may exceed 20 nm peak to peak in the x-axis, which is at the moment the major contributor to measurement uncertainty of the integral system.
The sensor is connected to the digital signal processor unit of the NMM-1 via a 16-bit analogue to digital converter (ADC).

2.3. Control and evaluation software

The system is operated using a specially developed Matlab toolbox. The convenient possibility of using existing Matlab algorithms and functions for data evaluation and visualization is ensuring maximum flexibility for system operation, what is needed to perform 2.5D surface metrology and 3D coordinate metrology with the same system. Besides using Matlab plotting and filtering functions, iterative algorithms were programmed for least squares fit of spheres and outlier elimination.

3. SYSTEM PERFORMANCE

The described system has been tested with several different probes for the measurement of diverse surfaces and proved its functionality in conventional STM mode, Weckenmann (2007a), and also for 3D single points and scanning measurement for coordinate metrology, Weckenmann (2007b).
The probing system resolution in radial direction is dependent on the used probe and workpiece material and the form of the probe tip. Typical is a resolution far below 1 nm at a nominal working distance between 10 nm and 100 nm. At line scans a repeatability of down to 3 nm (z-direction) and a lateral resolution of approximately 1 nm could be achieved, Weckenmann (2007a).

3.1 2.5D Surface Metrology

For 2.5D surface metrology the system has an impressive ratio between resolution and range that enables for nanometer resolved measurements with centimeter sized measuring ranges. Due to time limitations it is not practically feasible to scan the whole measuring range with highest resolution, but the system can be used for nanometer resolved distance measurement of small structures or larger objects that are separated by tens of millimeters.
Fig. 7 shows a high resolution measurement on a worn gauge block with a needle-like stainless steel probe. Clearly visible is the resolution in the nanometer order. Measuring time was approximately 15 minutes.

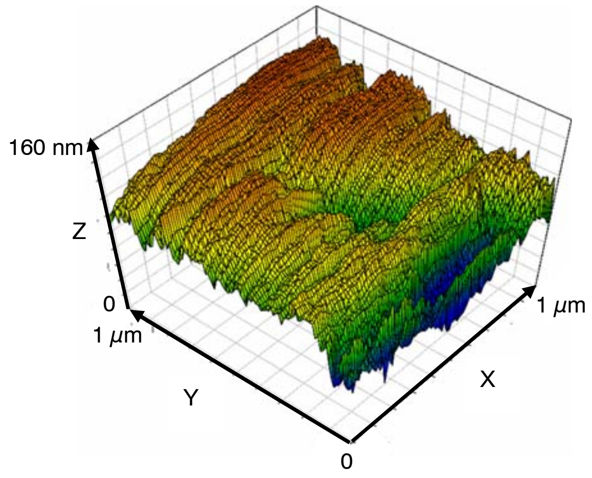

Fig. 7. High resolution 2.5D measurement of a worn gauge block.

Long range ability can be seen at fig. 7. A measuring range of 1 mm x 1 mm was realized on a ground Invar rod. The lateral and vertical resolution is still far in the sub micron area and could be further improved, if a longer measuring time is acceptable. Measuring time for the 1mm x 1mm scan was about three hours.
Fig. 8 shows the leveled surface. Before leveling the measured height variation in the total area was 19.8 µm.

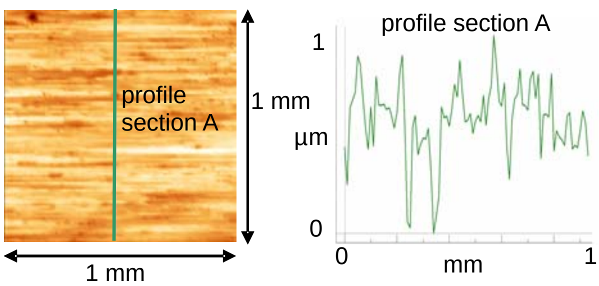

Fig. 8. Long range 2.5 D measurement of a ground Invar rod.

3.2 3D Coordinate Metrology

Major advantage of the introduced system is its capability for nanometer resolved 3D coordinate metrology without mechanical interaction with the workpiece.
To demonstrate the 3D ability of the probing system, an Invar ball bar was measured repeatedly with a spherical 0.3 mm hard metal probe, fig. 9. The Invar ball bar was custom made out of an Invar rod and two hardened steel spheres of class G5 (maximum form deviation 135 nm) provided by SKF GmbH, Germany. To fix the spheres on the bar at a long term stable distance, two holes (D=2.5 mm) were drilled into the Invar rod and the spheres were centred into these holes. Afterwards conductive adhesive was filled into the holes from the other side of the rod. With this method of assembly a direct and stable contact between the spheres and the Invar rod could be achieved without causing stress or

deformation of the spheres, what is likely with the conventional method of shrinking.
Due to the isotropic characteristics of the probe four scan lines from north pole to the equator, each of 1.5 mm length could be measured on the balls of 4 mm diameter. In the beginning of the repeated measurements thermally induced drift could be observed. After thermal soak out, the results of the distance measurement between the spheres stabilized with a standard deviation of 46 nm, fig. 10.

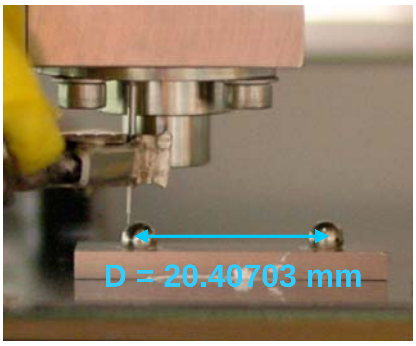

Fig. 9. Measurement of an Invar ball bar with a spherical hard metal probe (diameter 0.3 mm).

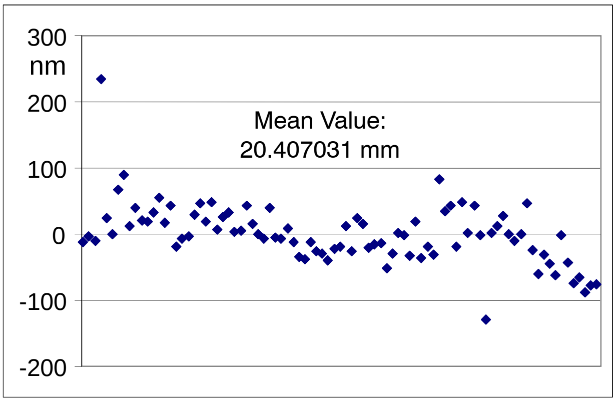

Fig. 10. Results of 90 repeated measurements of ball distance.

The standard deviation of 46 nm is caused by the probing system, but also the positioning noise and positioning uncertainty of the positioning system of more than 20 nm peak to peak and contamination of the ball bar and the probing sphere, as the measurements were performed under air atmosphere.
The time needed for 90 repeated measurements of the ball bar was nearly two days, so long term stability could also be shown. Before and after these measurements, further repeated measurements over several days were performed with same probe without any signs of wear or drift.
In further investigations 3D probing uncertainty will be evaluated similar to ISO 10360. This standard demands to probe a calibration sphere of 20 - 50 mm diameter, what is neither possible nor appropriate for micro CMMs, so it has to be modified for the use of smaller artefacts.
Also system performance will be improved by the application of an acoustic isolating hood, which will minimize movement of air around the system and thus decrease the influence of contaminations.

4. CONCLUSION AND OUTLOOK

A novel force less working probing system with electrical probing interaction for 3D micro coordinate metrology (patent pending) has been designed, set-up and successfully tested at a range of workpieces, demonstration objects and gauge blocks.
Advantages compared to commercially available tactile 3D micro probing systems are absence of static and dynamic probing forces and thermal load, no wear of the probing element or the workpiece, drastically enhanced robustness and flexibility, the additional possibility of 2.5D topography measurements, and quickly and easily changeable probes.
In future work the overall system performance is to be accurately determined by measurement comparisons with different commercial micro CMMs. Direct evaluation of system performance with the help of calibrated standards is limited due to the lack of appropriately accurate and large artefacts.
Further improvement of resolution and measurement uncertainty is expected by the application of a specially designed acoustically isolating hood which is currently under construction.

References:

Danzebrink, H.-U.; Koenders, L.; Wilkening, G.; Yacoot, A.; Kunzmann, H. (2006). Advances in Scanning Force Microscopy for Dimensional Metrology. *Annals of the CIRP, 55/2*, pp. 841-879, Paris, France.

Jaeger, G.; Gruenwald, R.; Manske, E.; Hausotte, T.; Fuessl, R. (2004). A Nanopositioning and Nanomeasuring Machine: Operation - Measured results. *Nanotechnology and Precision Engineering 2/2004(2)*, pp. 81 - 84, Tianjin, China.

Weckenmann, A.; Peggs, G.; Hoffmann, J. (2005). Probing Systems for Dimensional Micro and Nano Metrology. *7th International Symposium on Measurement Technology and Intelligent Instruments*, Huddersfield, UK, September 2005. - Index of Papers, pp. 199-206. and in: *Measurement Science and Technology 17*, p. 504-509.

Weckenmann, A.; Hoffmann, J. (2006). Construction and Evaluation of a traceable metrological long range Scanning Tunneling Microscope. *Book of Summaries*, p. 146, IMEKO XVIII WORLD CONGRESS (Metrology for a Sustainable Development), Rio de Janiero, Brazil, September 2006.

Weckenmann, A.; Schuler, A.; Hoffmann, J. (2007a). Development of a tunneling current sensor for a long range nano positioning device. *Book of Abstracts, p. 27*, 10th CIRP Conference on Computer Aided Tolerancing, Erlangen, Germany, March 2007.

Weckenmann, A.; Hoffmann, J. (2007b). *Long range 3D Scanning Tunneling Microscopy*, Annals of the CIRP 56/1 (2007), Dresden, Germany, August 2007.

van Vliet, W. P.; Schellekens, P. (1996). *Accuracy Limitations of Fast Mechanical Probing*, Annals of the CIRP 45/1 (1996), Como, Italy, August 1996.