

## MANUFACTURING METROLOGY – STATE OF THE ART AND PROSPECTS

**Weckenmann A.**

**(Kraemer, P. and Hoffmann, J.)**

Chair Quality Management and Manufacturing Metrology, University Erlangen-Nuremberg,  
Naegelsbachstr. 25, 91052 Erlangen, Germany  
Phone: +49-9131-85-26520, Fax: +49-9131-85-26524,  
E-mail: Albert.Weckenmann@qfm.uni-erlangen.de

**Abstract:** Manufacturing metrology is the prerequisite of quality management and process control and hence of enormous importance for economic manufacture of high-quality products. In order to support quality management and process control appropriately it has to keep pace with the developments in production (e.g. automation) and also modern products as well as their technology, e.g. nanotechnology. Additionally rising economic demands due to the global market push the development of manufacturing metrology.

The most important future trends for manufacturing metrology are holistic measurement, ease of use, miniaturization and economic benefits by improved speed, robustness and costs of measurement.

The article will show today's manufacturing metrology and the most promising developments for addressing the mentioned trends and demands.

**Key words:** Manufacturing Metrology, Quality Management, Computed Tomography

### 1. INTRODUCTION

Each kind of quality management and process control relies on quantitative information about products and processes. This information can only be gained by measurement. As a direct conclusion quality, but also costs of a process or product are strongly dependent on quality and cost of the quantitative information about it.

The quantitative information about quality is used for decision-making in conformity assessment of products or processes (Kunzmann 2005). The risk of false decision-making rises with coarser sampling and higher measurement uncertainties. In terms of an economic orientation, the costs of testing have to be balanced against the costs deriving from false decisions.

### 2. EVOLUTION OF MANUFACTURING METROLOGY

Modern manufacturing metrology was initiated by the changeover from artisan manufacture to mass production with interchangeable components in central Europe in the end of the 18<sup>th</sup> century. Whereas former craftsmen only had to ensure the function of individually manufactured devices by adjusting the components to each other, industry additionally had to ensure interchangeability of components to gain economic benefits from mass production and to enable offering of exchangeable spare parts. As a consequence it was not sufficient to compare and to rework two components to make them fit together, but the absolute dimensions of components had to be

manufactured and measured exactly enough to ensure the function of the assembly independently from the choice of the individual parts.

Dimensional measuring is always a comparison between the length to be measured and a standard of length, the length unit. For internationally comparable length measurements a common length unit is indispensable. The meter convention of 1875 provided this universal and internationally acknowledged length unit, the meter, which was at that time embodied by a prototype made from platinum-iridium, fig. 1.



Fig. 1. The meter prototype made from PtIr (source: Bosch Encyclopedia of Power Tools).

The prerequisite for internationally comparable measurements was established. In the following efforts were made first of all to reduce measurement uncertainty, Fig. 2.

Generally this is possible with three complementary approaches:

- reducing the uncertainty of the meter definition and its realization

- reducing the uncertainty in the definition of the measurement task
- reducing the uncertainty of comparing the length to be measured with the unit length

The first approach has to be followed by national metrology institutes (NMI) whose task is to provide realizations of the unit length that can be used by industry. An important step in this direction was the definition of the unit length with the help of a natural constant (velocity of light) and a very exactly measurable quantity: time. To transfer this meter definition to the shop floor, the time definition is realized using a Caesium frequency standard (atomic clock). Via frequency chains the frequency of an iodine stabilized Helium-Neon laser can be traced to the caesium standard. Afterwards Helium-Neon lasers can be traced to the iodine stabilized HeNe laser and used to set-up laser interferometer which can in turn be used to calibrate gauge blocks, scales or any other kind of precision length measuring equipment.

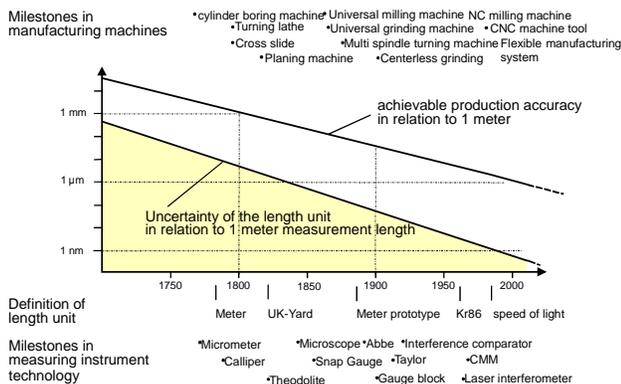


Fig. 2. Historical development of manufacturing and measuring uncertainty

The second possibility concerns mainly standardization and is therefore subject of ISO, the international standardization organization. Contribution from academia and industry is needed here to ensure the practical usability of standards and to stimulate and promote the development of practically needed standards.

The third point is a matter of instrumentation and is mainly pursued by developers and manufacturers of metrology equipment. Here the evolution of metrology is most obvious.

In the early days of manufacturing metrology almost only two-point measures were specified and evaluated due to the early stage of measurement devices and also the lack of modern evaluation methods. Generally measurements were taken one-dimensionally, i.e. only distances between two points were evaluated individually without regard of other measures. With rising demands to accuracy it was found that two-point measures might be ambiguous, e.g. when measuring the diameter of a shaft with non-negligible form deviation. This was addressed by the development of advanced metrology devices: measuring microscopes and

profile projectors on one hand giving the possibility of two-dimensional measurements in a plane section, and roughness and form measuring equipment on the other hand, giving quantitative information about the degree of imperfection of geometric features on workpieces.

The next major step in manufacturing metrology was the incorporation of electronic components such as read outs, inductive displacement sensors, RC-filters or pen recorders. Some of these electronic gadgets facilitated measurements or their evaluation, others served for further improvement of accuracy and resolution. The introduction of photo-electric devices and advanced light sources, like the Helium-Neon Laser, pushed optical measuring technologies forward and enabled for a not foreseen level of accuracy that was also used to improve the meter definition in 1960 in the way mentioned above. The meter was not longer the length of an embodied standard, which could alter with time, but it was new defined with the help of a natural constant: the wavelength corresponding to a certain energy difference in the electron sheath of krypton.

After this electro-optic revolution of metrology, the next global trend was coordinate metrology. With coordinate metrology the philosophy of measurement changed drastically. While in the time before many measures were taken independently on one workpiece, with coordinate measurement machines rather points on the workpiece surface instead of measures were taken, giving the possibility of evaluating a number of different measures and features out of a representative set of probed points. Advances in computer technology opened the way for much more complex evaluations, like the application of non-linear filtering, new evaluation criteria (e.g. tangential elements, least-squares features, maximum inscribed or circumscribed features, etc.) and accuracy was improved continuously. At the turn of the millennium an axis resolution of 0.1 μm and scanning measurements were state of the art. CAD based programming and evaluation already entered into coordinate metrology and many fields of optical metrology and helps to reduce the effort for programming and data evaluation.

### 3. STATE OF THE ART

Today two-point measures are still widely used. They are quick, easy and cheap to assess and are often sufficient to ensure the function of a product or to control a process. Especially in the shop floor two-point measures taken with simple devices like calipers or micrometer screws are still dominant, because of their efficiency and ease of use.

On the other hand it is very tedious or even impossible to check more complex attributes of a workpiece (e.g. volume of a complex shaped cylinder head, curvature of formed sheet metal parts) or to do reverse engineering with the help of independent two-point measurements.

Often much higher point densities are needed, which can be achieved with optical measurement (e.g. fringe projection measurements or white light interferometry), but sometimes also with high-speed scanning coordinate measurements, which are nevertheless still the most

universal measurements. Computer based techniques for compensation of dynamic errors helped to accelerate scanning speeds up to 500 mm/s. As a further improvement of measuring speed does not result in significant advantages for the time needed for measurements, emphasis is now put on the reduction of time needed for programming the machine and for analysis of measured data.

### 3.1 Fringe Projection

When it comes to measure complex freeform surfaces for inline process control or the reverse engineering of car body work created by designers or aerodynamic shapes developed in wind tunnels, two-point measures are not suitable any more. Here fringe projection offers fast, holistic and contact free sampling of complex surfaces with high point densities in relatively short time.

The 3D data acquisition of a fringe projection system is based on the triangulation principle, fig. 3. One or more cameras record a parallel fringe pattern, which is projected on the measuring field, under the calibrated triangulation angle  $\alpha$ . According to the triangulation principle, the phase difference between the observed picture and the picture recorded by measuring a calibrated plane (reference plane) is proportional to the position  $\Delta z$  in normal direction to this reference plane. This means, the distance  $\Delta z$  is depicted as displacement  $\Delta x$  on the camera.

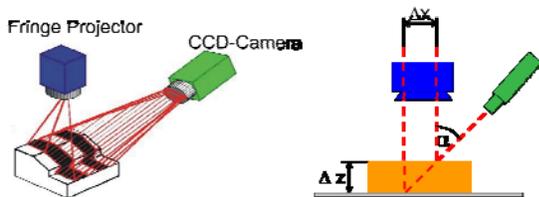


Fig. 3. Fringe projection system – (a) setup and (b) triangulation principle

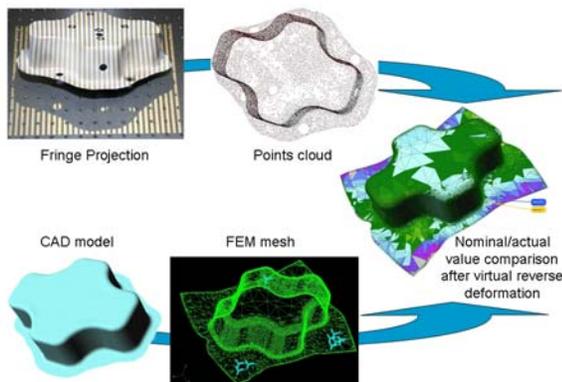


Fig. 4. Virtual reverse deformation of formed sheet metal parts

In combination with the virtual reverse deformation (Weckenmann 2007b), quick and contact free

measurements of formed sheet metal without fixation or clamping can be performed by using fringe projection systems. By the use of finite element methods the shape in assembled state can be simulated and features, e.g. relevant for the assembly process, can be extracted and evaluated, fig. 4. As a result of this the inspection process chain of sheet metal parts is shortened and automated simultaneously. Future procedures for automating the process will even offer the possibility of 100% testing.

### 3.2 White light interferometry

If the topography to be measured is very flat or smooth, if access to the surface is only possible from one direction and if sub-micron resolution is demanded, white light interferometry is often used, e.g. in electronics, optics and also automotive industry.

The principle of white light interferometry relies on the wave properties of light, i.e. it is possible to calculate phasing and thus differences in optical path length from the intensity, like it is also done in laser interferometry.

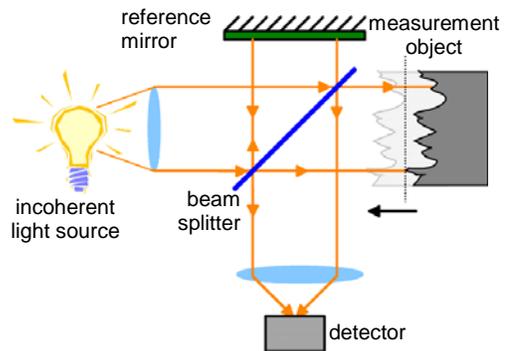


Fig 5. Configuration of a white light interferometer according to Michelson

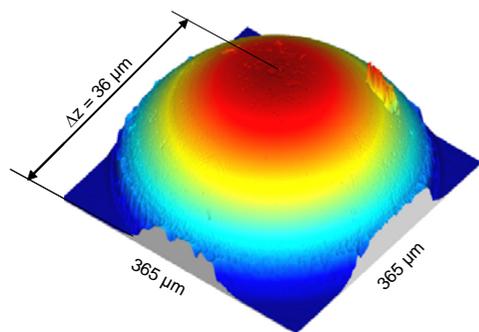


Fig. 6. Microlens measured with a white light interferometer

To extend the small area of unambiguity in laser interferometry and to enable the measurement of rough technical surfaces, a light source with a small coherence length (e.g. 3  $\mu\text{m}$ ) can be used. As a result of this, interference can only be observed if the difference between the reference path of light and the measured path of light is

less than the coherence length. The interference contrast shows its maximum at equal lengths of both paths. The optical path can be setup up e.g. according to Michelson (Fig. 5) or Mirau.

By varying the reference or measurement path of light so that the plane of maximum interference contrast passes through the whole extension of the workpiece in beam direction, the maximum interference contrast and therefore the position  $z_0$  can be measured for each surface point of the measurement object in beam direction. In the orthogonal plane to the beam direction the position of the measured point is determined by the pixel of the CCD sensor onto which it is projected. With such a system it is possible to measure 2.5D topographies by uniaxial scanning. Commercial white light interferometers achieve resolutions down to 0.01 nm in beam direction, the lateral resolution depends on CCD resolution and field of view.

White light interferometers play an important role in the quality control of optical devices (e.g. micro lens arrays, Fig. 6), electronic circuitry, but also sheet metal or honed or ground surfaces.

### 3.3 Coordinate Metrology

With the propagation of affordable and powerful computers coordinate metrology became more and more important for industrial metrology. Coordinate metrology is the most universal measurement technology in mechanical manufacturing. Coordinate measuring machines (CMMs) acquire points on the surface of the workpiece rather than measuring features directly. From this set of points diverse geometric features may be calculated which are afterwards used to evaluate the compliance of the workpiece with the specification.

Today there exist many different types of coordinate measuring machines with differing sizes to measure small objects like housings of mobile phones as well as large objects like engine blocks for cargo ships or bearings for wind generators. Portable systems with position measurement based on triangulation (set-up e.g. with laser trackers) can be beneficially used for measuring extremely large objects, such as complete ships or aircrafts and miniaturized CMMs are able to measure micro parts with nanometer resolution. Special robust CMMs can be used to measure in the shop floor in harsh environment next to manufacturing machines.

The first contacting (tactile) probes to detect the workpiece surface were so-called touch-trigger probing systems that could be used to trigger a read-out of the coordinate axes upon contact with the workpiece (first implementation 1972 by Sir David McMurtry). After one point is probed, a touch-trigger probing system has to be withdrawn from the workpiece surface to be able to trigger again.

In 1973 Zeiss presented the first measuring 3D probing system Zeiss MT. With this technique the amount of stylus deflection due to contact with the workpiece could be measured and so continuous probing of surfaces (scanning)

became possible.

The MT, like many modern measuring probing systems, consists of three stacked axes, each of them including a length measuring system and an actuator.

The successor of the MT system, the Zeiss VAST Navigator technology features a probing system and an associated advanced high speed scanning technology with compensation of dynamic errors. High acceleration during scanning introduces heavy dynamic loads to the machine axes, the probing system and the stylus and cause dynamic bending of these components, fig. 7. Additionally these dynamic forces may influence the probing force significantly. These two sources of errors compromise scanning accuracy at high scanning speeds and are compensated for with the Navigator system independently from the feature to be measured.

The VAST probing system has active and controlled probing force generation with electromagnetic actuators instead of commonly applied springs and mechanically compensates for changes in probing force due to centrifugal forces. Compensation of dynamic bending is achieved by D-CAA (dynamic bending computer aided accuracy): the location and acceleration dependent bending behavior of machine and probe geometry are mapped and embedded into the machine control for correction. With these methods dynamic errors can be limited to less than 1  $\mu\text{m}$  at scanning speeds of 100 mm/s and more.

Another feature of the VAST Navigator system improving scanning efficiency is a software assistant that determines the optimum measuring speed in dependence of the geometric feature to be measured, its tolerance, the stylus and the used CMM type.

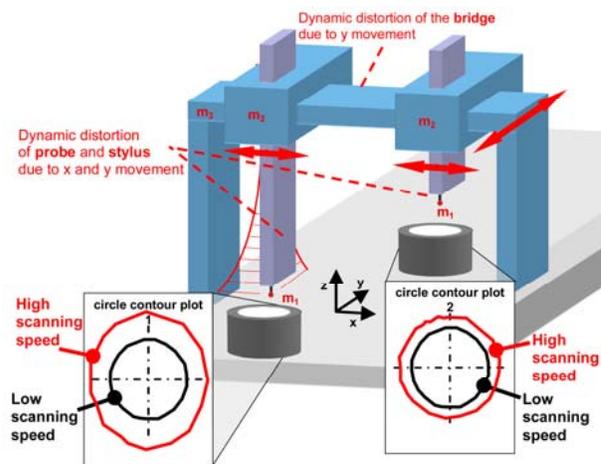


Fig. 7. Dynamic bending correction (Imkamp 2004).

Another high-speed scanning system is available from Renishaw, the Revo probing system and the Renscan scanning technology. The Revo system is a probing system with integrated dynamically balanced high-speed two-axes articulating head. With this set-up cylindrical features can be scanned without accelerated movement of the CMM – it only has to move with constant velocity on a straight line, Fig. 8. The circular movement is done by the probing

system, which has by far better dynamic properties, than the bulky CMM. With the Revo system scanning speeds up to 500 mm/s are possible.

For additional compensation of dynamic errors the Renscan technology is used. There a feature is measured once slowly and once with high scanning speed. The mapped difference between these measurements can be used for compensation of sequent high speed measurements of the same feature on other parts at the same position in the measuring range of the CMM (feature based compensation).



Fig.8. Revo Scanning System (source: Renishaw)

With the introduction of the mentioned high-speed scanning technologies measuring time can be reduced significantly, but preparation, clamping and programming time remain the same and thus become more and more important for the overall inspection time. In future efficiency improvement of these peripheral actions will help better for the reduction of inspection effort, than a further reduction of the measuring time itself.

#### 4. FUTURE NEEDS AND TRENDS

Generally spoken, development in metrology always means to extend the degree of information that can be gathered about an object, or to reduce the costs per unit of measured information. This development can be seen today first of all in the following future trends and new applications:

- holistic measurement (multi-sensor metrology, integral measurement with CT, 100% testing)
- Micro / Nano metrology
- cost reduction of standard measurements (quicker, cheaper, more robust and easier to use)

The today used tactile methods are to be complemented or partly replaced by optical 3D measurements depending on needed accuracy and surface properties since they offer the possibility to acquire more points in shorter time. These higher point densities will lead to shorter inspection times in association with increased reliability of the acquired information. Challenging is still to raise the robustness of optical metrology towards optical properties of the workpiece and to improve the ease of use in a way that even unskilled

personnel is able to achieve valid results with small uncertainty.

#### 4.1 Multi-sensor Metrology

Multi-sensor CMMs make it possible to test an extensive range of quantities, e.g. geometric and dimensional, mechanical, electrical, optical or material properties.

To improve quality control, especially for micro parts, the combination of different modern analytic technologies, such as AFM (Danzebrink 2006), with established measurement techniques, like optical microscopy and coordinate metrology is applied. The integration of different sensor principles into one machine makes it possible to gather holistic information about all relevant attributes of modern parts, assemblies and products and to merge this information into one common coordinate system.

To get a first overview of the workpiece to be measured a measuring system is needed that helps to find details to be tested or to determine the position of different microparts with respect to each other. The measuring range of overview sensors is rather big and the resolution low. In the actual measurement this overview system is used to navigate the other sensors integrated in the multi-sensor system. Optical systems based on image processing recommend themselves for this task. If an automatic navigation is needed, systems based on fringe projection, white light interferometry or videomicroscopy can be used, fig. 9.

Often, the size of the workpiece is very large compared to the resolution needed to test fine structures on surfaces. Data from fast scanning optical sensors, which are used as overview system, has to be combined with measured data of higher resolution. To gain information from data measured with different sensors, a correct and exact integration into one coordinate system has to be done. The transformation has to be carried out not only for the geometric measuring data, but also for information like e.g. temperature.

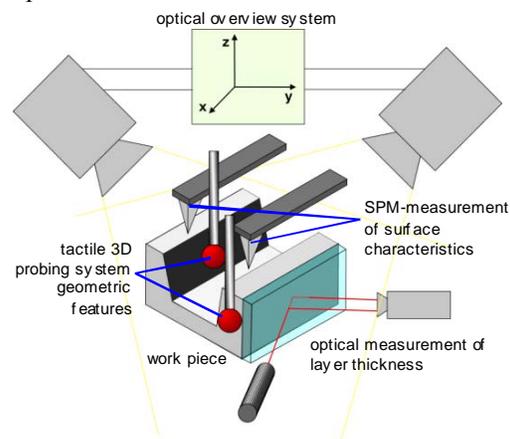


Fig. 9. Multi-sensor metrology for holistic measurement  
The diversity of sensors applied in multi-sensor CMMs solve a variety of measuring tasks such as: form and

positions of 3D standard geometric features with a size of less than 1 mm, surface texture and roughness in the nm or sub-nm domain, thickness of transparent and opaque layers. Depending on the kind of sensor also interior features and non-dimensional features may be measured, if they are important for the function of the part or compensation of environmental influences.

There are different setups for multi-sensor CMMs, 2.5D and 3D. Typically 2.5D systems are set up out of a plane scanning system and various 1D probing systems, similar to many conventional topography and surface roughness measuring systems. 3D systems on the other hand are mostly set up according to larger CMMs with modifications especially in the coordinate axes to improve resolution and to reduce measurement uncertainty.

Future challenges for the multi-sensor technology lie in the fusion of inhomogeneous data from different sensors. Unsolved problems are the combination of measurements taken with sensors with vastly different resolution. The automatic navigation of sensors in a multi-sensor CMM will also be part of future research.

#### 4.2 X-Ray Computed Tomography

Computed tomography offers completely new possibilities. With a tomographic measurement it is possible to analyze the whole volume of the workpiece, so detection and analysis of conventionally not accessible features with micrometer accuracy is possible.

The basic principle of X-ray computed tomography relies on attenuation of high energy radiation due to interaction with material. During the measurement process the measurement object is rotated, projections are taken at defined angle positions and saved to the image stack. From there the volumetric 3D model of the measurement object is reconstructed by mathematic algorithms, Fig. 10.

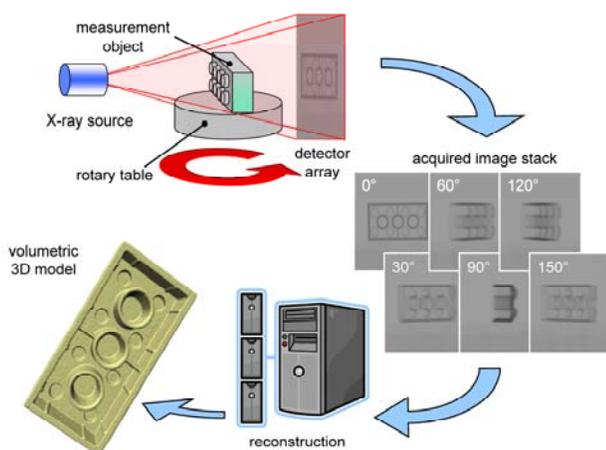


Fig. 10. Basic principle of computed tomography

The main advantage of computed tomography for industrial manufacturing metrology is that a volumetric model representing the whole measurement object is acquired by a single measurement lasting from few minutes

to hours depending on the workpiece complexity.

The measurement itself runs completely automatic which qualifies the technology for process control. Programming effort is very low as nearly always the entire measuring volume of the CT is measured. With the help of modern analysis software not only the quantitative evaluation of standard geometric features known from coordinate metrology but also the creation of virtual cross sections (fig. 11) to detect hidden defects like blow holes or bubbles in casted parts is possible. The volumetric model can be used for nominal/actual value comparisons of the whole workpiece and typically features a high point density (Bartscher 2007).

Some modern multi-sensor CMMs combine tactile, optical and tomographic inspection methods which offers the possibility of holistic measurements of workpieces with micrometer accuracy. The combination of the advantages of the different technologies will lead to faster, more robust and more reliable measurement results.

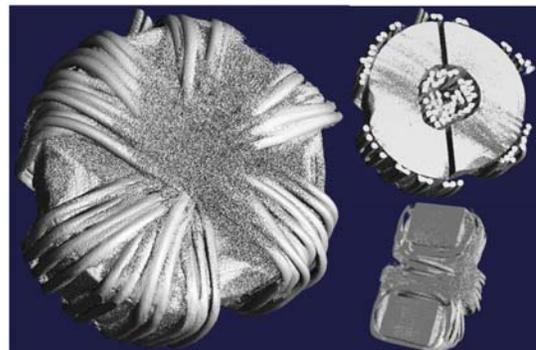


Fig. 11. Exemplary CT measurement of an encapsulated coil with two virtual sectional views (right side).

#### 4.3 Micro and Nano Metrology

The demands to manufacturing metrology are set by production, so metrology has to follow the trends of production engineering. Two of the most important trends in production engineering are miniaturization (e.g. implantable insulin pumps, cameras for mobile phones, etc.) and the incorporation of micro and nanotechnology into conventionally sized products, e.g. easy-to-clean surface modifications, embedded systems, etc. Modern manufacturing metrology has to support these developments and explore new dimensions. The new tasks are manifold and addressed by bottom-up and top-down approaches. Bottom-up is the modification of analytical tools from materials science or solid matter physics (e.g. scanning probe microscopy) for metrological purposes; top-down is the miniaturization of conventionally sized metrology devices, such as CMMs, for the measurement of micro features.

The bottom-up approach is especially useful for nanotechnology, whereas in microtechnology the top-down approach is dominant.

Scanning probe microscopy had its first applications in materials science, chemistry and micro biology as

qualitative imaging tool. To qualify it for metrological purposes first of all linearization of the scanner, calibration of scanner and tip and long term and thermal stability had to be improved considerably. This was done by integration of precision length measuring systems, such as capacitive gauges or laser interferometers and the development of standards for tip characterization, lateral and vertical calibration. Today several commercial and experimental metrological SPMs are available. The actual trend is here to improve and facilitate calibration and to extend measuring ranges.

An important example for the top-down philosophy is the miniaturization of coordinate measuring machines. This demands for improved axes resolution and miniaturized probing systems with better repeatability and resolution and much smaller probing elements and probing forces (Weckenmann 2005). Machines constructed in this manner are available from different CMM manufacturers and usually additionally comprise an optical sensor for navigation of the delicate tactile micro probe to avoid collisions with the workpiece.

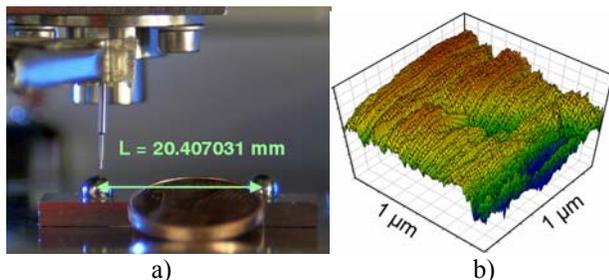


Fig. 12. Measurements performed with a long-range nanomeasuring machine.

Mixtures of both approaches have been realized by using probe-sample-interactions known from scanning probe microscopy for miniaturized 3D probing systems and high precision 3D metrological positioning stages with some ten millimeters range. An example for this hybrid approach has been set-up using an electrical probing interaction. By abandoning the need for force transmission via the probe stylus and getting rid of gravitational and inertial influences a lot of limitations for the design of the probing element and stylus have become obsolete, like the need for a mechanically stiff stylus, symmetric moment of inertia and mass distribution of the stylus, or a rigid connection between stylus and the contact detecting sensor. Benefits from that are the applicability of spherical 3D touch probes, but also needle-like 2.5D surface measuring probes and even complex stylus trees containing both, what enables for a variety of measurement tasks. Fig. 12a shows a nanometer resolved coordinate measurement (length of a micro ball bar), fig. 12b a micro roughness measurement on a gauge block performed with this device (Weckenmann 2007a).

Environmental effects are more significant for micro and nano measurements, than for macroscopic measurements due to the finer resolution and the often very

large ratio between measuring range and resolution. This is even more important, if relatively large distances are to be measured with nanometer resolution. Conditioning of the measuring environment is costly and only feasible to a certain degree. Computer based non-linear correction or compensation methods will help in future to reduce this effort and to improve stability of measuring results.

For conventionally sized products with functional features using micro- or nanotechnology, still the linkage from macro to nano size has to be established. Due to a lack of metrology techniques that are useful for small and also large dimensions, the solution for this problem is very likely to lay in multisensorics and dimensionally correct and information technologically efficient data fusion.

## 5. CONCLUSION AND OUTLOOK

On the one hand, measurement technology is often seen as an expense factor which has to be minimized as far as possible. On the other hand, measurement results have to feature a defined accuracy; otherwise they are worthless in terms of decision-making. With regard to an economic optimization, measurement technology must provide satisfactory information about products or processes for an optimum of costs. Therefore, it has to be defined how much information about a product or a process is necessary to assure functionality. There will always be a tradeoff between the amount of reliable information and the costs spent for gaining this information by measurements. It has to be ascertained which measuring technique is qualified best for a particular application by the use of cost-benefit-analyses. Against this background, there are many questions to be answered, e.g. whether it is better to invest money in the education of employees or in automation of measurement processes.

Currently still most complex inspection measurements in industry are done with the help of coordinate measuring machines. Due to the long measuring time only samples of the production can be taken at which only the most important features are measured and evaluated. Also operation of most CMMs requires skilled and thus expensive and slender staff. With the help of modern holistic measurement technologies, e.g. computed tomography, measurement and – maybe much more important – programming and preparation effort for the measurement will be reduced and the reliability of the measurements will increase due to much higher point densities. The faster and more robust inspection could even make it possible to integrate the measurement process into the manufacturing process. This would enable for automatic re-working of components without significant time loss and costs for clamping, unclamping and transport. The possibility of measuring conventionally inaccessible interior features will vastly reduce destructive testing.

To put it in a nutshell: today advances in metrology reduce the cost per unit of measured information and advances in quality control help to limit the measuring effort needed to ensure the function of parts and processes.

In that sense metrology yields an economic benefit instead of being a mere cost factor, fig. 13.

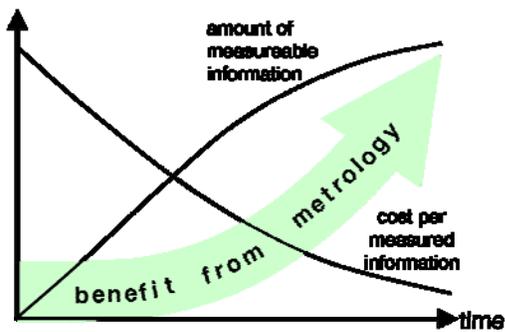


Fig. 13. Benefit from Metrology

## 5. ACKNOWLEDGEMENTS

A. Dietlmaier, L. Heidemann, J. Weickmann, DFG for funding the Collaborative Research Centers 396 and 694, German Federal Ministry of Education and Research (BMBF) for funding the ProNanoMess project

## 6. REFERENCES

- Bartscher, M.; Hilpert, U.; Goebels, J. & Weidemann, G. (2007): Enhancement and proof of accuracy of industrial computed tomography (CT) measurements, *Annals of the CIRP*, Vol. 56/1/2007.
- Danzebrink, H. -U.; Koenders, L.; Wilkening, G.; Yacoot, A. & Kunzmann, H. (2006). Advances in scanning force microscopy for dimensional metrology, *Annals of the CIRP*, Vol. 55/2/2006.
- Imkamp, D., Mueller H. & Matczak, B. (2004). Technical progress in tactile probing technology "Navigator Scanning", *VDI-Bericht 1860, 8<sup>th</sup> IMEKO ISMQC*, Erlangen, Germany, October 2004
- Kunzmann, H.; Pfeifer, T., Schmitt, R. Schwenke, H., Weckenmann, A. (2005). Productive metrology – Adding value to manufacture, *Annals of the CIRP*, Vol. 54/2/2005.
- Weckenmann, A.; Peggs, G. & Hoffmann, J. (2005). Probing systems for dimensional micro and nano metrology, *Meas. Sc. and Tech.*, Vol. 17, pp. 504-509.
- Weckenmann, A. & Hoffmann, J. (2007a). *Long range 3D scanning tunneling microscopy*, *Annals of the CIRP*, Vol. 56/1/2007.
- Weckenmann, A.; Weickmann, J. & Petrovic, N. (2007b): *Shortening of Inspection Processes by Virtual Reverse Deformation*, 4<sup>th</sup> International Conference and Exhibition on Design and Production of Machines and Dies/Molds, Cesme, Turkey, June 2007.