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# AUTOMATIC EXECUTION OF INSPECTION PLANS FOR KNOWLEDGE-BASED DIMENSIONAL MEASUREMENTS OF MICRO- AND NANOSTRUCTURED COMPONENTS

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**Abstract:** Due to the fast advancement of manufacturing technologies for micro- and nanostructured components [1] the need for sophisticated inspection methods increases. The paper on hand discusses the prerequisites for automatic execution of inspection plans. Main goal is to enable automated dimensional measurements of micro- and nanostructured components instead of executing functional tests. Besides reducing manufacturing cost this approach enables the setup of a closed quality loop which allows a higher level of efficiency. It provides a constant feedback to the manufacturing processes and to the design process. Based on the latest state-of-the-art the setup and operating principle of a closed quality loop for dimensional inspections is described. Vital part of the closed quality loop is a multisensor system consisting of adaptive, intelligent sensors with cascaded measuring ranges. The paper provides a novel and consistent overall view of dimensional inspections of micro- and nanostructured components and how they will be executed in the future. This paper shall deliver a significant contribution to the birth of industrial nanometrology [2] which must overcome the limitations of research oriented nanometrology.

**Keywords:** inspection planning, micro- and nanometrology, dimensional measurements, multisensor measurements.

## 1. INTRODUCTION

Recently a study on the international state-of-the-art in the field of micro-production technologies has been carried out [3]. It emphasises explicitly the importance of quality assurance and measurement technology. Thereby the need to lead back the results of inspection processes for future quality assurance actions or manufacturing process improvements is highlighted. There is a large lack of appropriate inspection technology in industrial production of micro- and nanostructured components [4], [5].

State-of-the-art are functional test which are usually executed after the assembly of the whole micromechanical product [6], [7]. Approximately 80 percent of the value creation occur after the wafer level [8]. Thus significant cost can be saved if the microstructured components can be inspected on wafer level after the structuring processes e.g. etching. Considering wafer bonded components for example the yield after the decollating of bonded wafers amounts currently to 60 - 80 percent [6].

The need of appropriate inspection methods is also documented by the setup of various research projects aiming at the further development of inspection technologies, for example priority research programme SPP 1159 „New Strategies of Measurement and Inspection Technology for the Production of Micro Systems and Nanostructures“ 2004-2010 funded by the German Research Foundation (DFG). Additionally the German Federal Ministry for Education and Research (BMBF) set up a framework programme entitled Micro Systems 2004-2009 which has a volume of approximately 260 million euros. Some examples for initiated BMBF projects are the projects „MikroPrüf“ 2002-2006 [6], “3D-Mikro” 2005-2007 [9], “3D-µMess” 2005-2007 [10] and „ParTest“ 2005-2007 [8].

A further aspect for the success of industrial micro system technology has been outlined by the German Electrical and Electronic Manufacturers' Association (ZVEI). This aspect is the necessity to provide CAD tools and CAD libraries in order to enable an integrated and verifiable design process from the system level via the micro component to possible process influences. Thereby the integration of suitable simulation tools can not be omitted. The aspect of utilising special CAD tools for designing micro systems for example SoftMEMS CAD Design Environment or ConventorWare (suite of MEMS design tools) is taken into account in the subsequently described closed quality loop. The data transfer between the different process stages i. e. between CAD stage and inspection planning stage is realised through standardised data formats such as STEP and QDAS. Thus as long as the newly emerging CAD tools allow to export design data in such formats they can replace or supplement the previously used CAD tools without additional efforts.

## 2. INSPECTION PLANNING

The term inspection planning is defined in the VDI/VDE/DGQ guideline 2619 [11]. Regarding the overall system described in this paper two aspects of inspection planning should be distinguished. The design-based inspection planning applies the knowledge attained during the design stage. The knowledge-based inspection planning comprises the following three items:

- derivation of dimensional inspection features from the function of the micro- or nanostructured component [7],
- automatic parameterisation of the probing sensors according to the existing measuring conditions and
- determination of an optimal inspection strategy whereby the knowledge of the characteristics of the available sensors is taken into account.

Thereby the term optimal inspection strategy refers to minimal traverse path, minimal measuring time and a minimal degree of wear (for example AFM tip (atomic force microscope) in contact mode). This is enabled through the precise knowledge of the position and size of the area of the measuring object where the feature to be inspected is located.

## 3. CHALLENGES FOR DIMENSIONAL MICRO- AND NANOMETROLOGY

This paper focuses on dimensional inspection of micro- and nanostructured components. This is very important for inspections on wafer level. Thereby predominantly micromechanical products and all other products are inspected, for which geometry and size of structures are suitable to evaluate their functionality.

In general inspections of such components do have to cope with a huge number of inspection features, which can be up to 100,000 at one part only. Typically very small features for example 100 nm wide structures are distributed over a large area of several square millimetres or even several square centimetres. Any inspection technology has to span more than one scale of dimension [12], [13]. This is a challenging task.

Moreover the critical dimension is constantly decreasing. Exemplary the International Technology Roadmap for Semiconductor (ITRS) [14] specifies 21 nm as current maximum value for placement errors of microstructures on photomasks. As Fig. 1 illustrates there is a huge variety of different sensing principles for measuring micro- and nanoscale dimensional features. Each method has its own individual advantages and limitations. In order to perform 3D coordinate measurements within the micro- and nanometre range a combination of different sensors must be utilised.

When inspecting nanometric features surface metrology and dimensional metrology melt together. This can be illustrated by considering the proportion of volume to surface of geometrical primitives for example sphere, cube, plane. For shrinking dimensions of micro- and nanostructured components the surface decreases only quadratically whereas the volume decreases cubically [15].

Besides this issue the interaction between the sensor for measuring the component and the measuring object itself becomes crucial with shrinking dimensions. Exemplary at AFM measurements the recorded raw measuring data have to be interpreted respectively deconvoluted according to the existing physical as well as geometrical interactions between tip and sample [16], [17]. Otherwise wrong measuring results will be attained.

A further issue are suitable tolerances for micro- and nanostructured components. The simple down-scaling of the existing general tolerances for macroscopic features can not be the solely solution. The so called “Goldene Regel der Messtechnik” (“Golden Rule of Measurement Science”) states that the measuring uncertainty should be ten times smaller than the tolerance of the feature to be inspected.

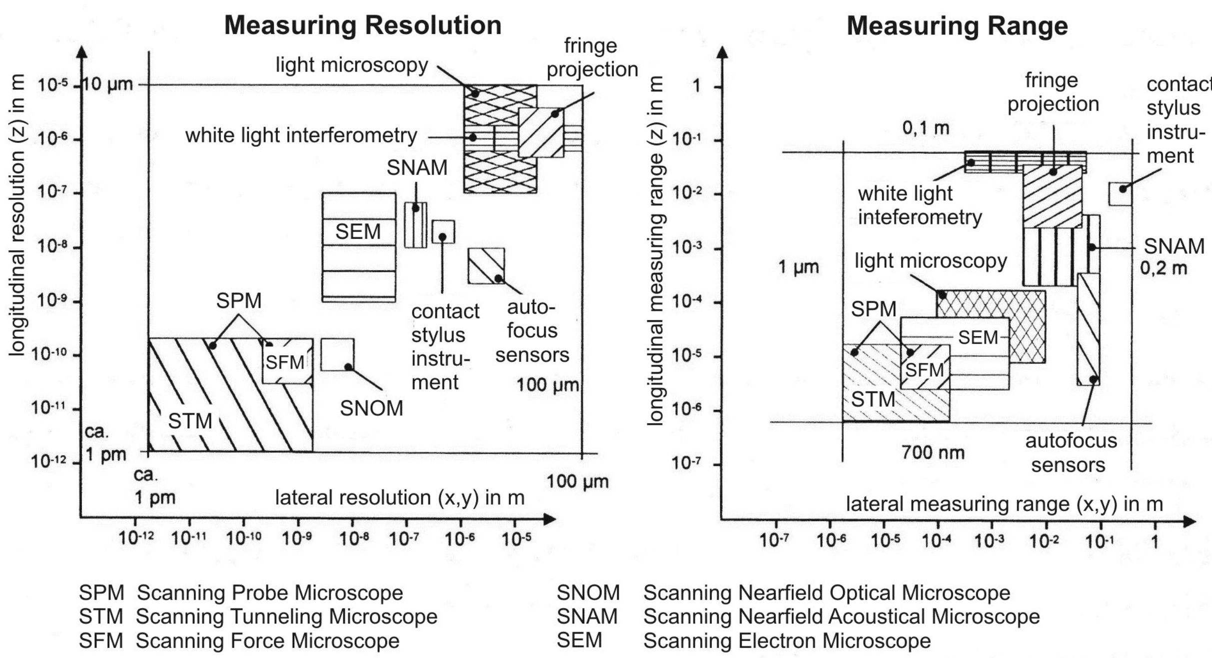


**Fig. 1: Resolution and measuring range of typical measuring methods for micro- and nanoscale components [15]**

Considering a lateral tolerance of 2 nm for measuring the width of a structure the maximum allowable measuring uncertainty according to this rule amounts to 0.2 nm. Current values for measuring uncertainty for measuring the width of structures for example at photo mask width standards amounts to 15 nm (k=2) for SEM measurements and to 24 nm (k=2) for optical measurements with an UV transmission microscope [18].

During the last ten years tolerance systems, measuring strategies and parameters for describing the properties of micro systems did not change essentially [15]. However, there has been constant improvement of measuring machines and sensors as well as of manufacturing processes. The well known methods and procedures for inspecting macroscopic features respectively the working principles they stand for, should be investigated regarding their applicability in inspecting purposeful features at micro- and nanostructured components. Many of the known inspection strategies in dimensional metrology are not likely to be of use under these conditions but some may prove being very useful.

Finally there are three further criteria for dimensional measurements of microscale components which have been described by Storz [12]. They apply for nanoscale components as well. They are:

- automatic execution of the measuring process,
- short measuring time as critical factor for the utilisation in industry and
- no change or destruction of the inspected structures.

Moreover, the fixing of the measuring object without introducing stress has to be listed. Bader [19] indicates freeze clamping, rheological fluidic fixing, needle fixing cushion and electrostatics as possible methods.

## 4. SETUP OF A CLOSED QUALITY LOOP

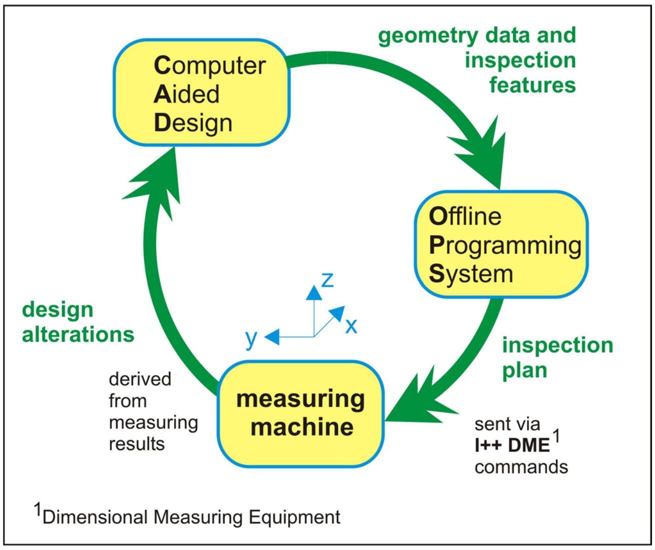


**Fig. 2: General setup of a closed quality loop for dimensional measurements with coordinate measuring machines (CMM)**

The large number of inspection features at dimensional measurements in the micro and nano range entails a need for a lossless information flow along the process chain [20]. Thereby the process chain comprises CAD and CAQ and is characterised by neutral interfaces. From the viewpoint of quality assurance the process chain corresponds to a small closed quality loop (Fig. 2). Its principle applies not only for measurements in the macroscopic scale but also for measurements in the micro- and nanoscale. In [21] a detailed description of the application of this principle for inspecting micro- and nanoscale features is given.

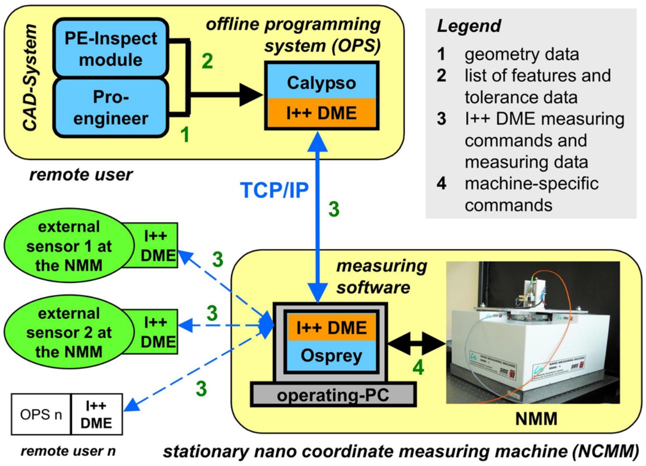


**Fig. 3: Closed process chain for dimensional measurements of micro- and nanostructured components utilising the NMM**

The state-of-the-art is represented by the recently accomplished adaptation of the closed process chain to the nano positioning and nano measuring machine (NMM) [22] (see Fig. 3). Thereby, novel principles of knowledge distribution and novel inspection strategies have been outlined. The paper on hand develops those ideas further.

As Fig. 3 shows the closed process chain starts with the design of micro- or nanostructured parts or components with the CAD system ProEngineer. The geometry data are saved as STEP-file. The module PE-Inspect is used to export the list of inspection features as QDAS-file. Both files are imported in the offline programming system (OPS) namely Calypso. The OPS is used to perform the inspection planning which can be done offline. Typically the OPS supports the neutral I++/DME (Dimensional Measuring Equipment) interface [23]. Consequently it allows to initiate the automatic execution of the inspection plan. Thereby the OPS and the measuring software are communicating bidirectionally via the TCP/IP protocol.

The measuring software namely Osprey incorporates the server side of the I++/DME interface. The OPS transmits the previously created measuring sequence via the I++/DME interface to the measuring software. The I++/DME server of the measuring software interprets the received I++/DME commands as machine-specific commands for the NMM. These commands are directly executed by the NMM. The recorded measuring raw data are corrected e.g. sensor specific corrections, machine specific corrections. The correct measuring data are sent back to the OPS where the comparison between CAD data and actual measuring data is performed. Due to the observed deviations design alterations or adaptations of manufacturing processes are initiated.

Many of the I++/DME commands involve the utilisation of the probing sensors of the measuring machine. If tactile sensors are to be used the communication between measuring software and sensor utilises the known standard interfaces for tactile sensors e.g. Renishaw interface. If optical sensors are deployed the measuring software communicates via the Optical Sensor Interface Standard (OSIS) with these sensors. Currently over 200 types of optical sensors are on the market. Many sensor principles are available whereby each of them has advantages for specific measuring tasks. Thus besides some widely spread sensor types there are many niche sensors. The motivation for the initiation of OSIS lies with the complex integration of optical sensors in coordinate measuring machines (CMM) and with the related high economical and technical risks for CMM manufacturers and sensor manufacturers [24]. After three years of intensive collaboration of about 25 companies from Asia, America and Europe the first version of the documentation of OSIS has been published in 2004 [25].

The closed process chain for dimensional inspection of micro- and nanoscale components incorporates the I++/DME interface instead of the Dimensional Measuring Interface Standard (DMIS) [26] for different reasons. Firstly the interoperability of different measuring machines with measuring sequences written in DMIS is not generally given. Secondly DMIS has only very limited capabilities for deploying optical sensors. Thirdly DMIS allows no online communication between the measuring machine and the OPS. However the utilisation of DMIS for offline inspection planning and archiving inspection plans will continue.

Based on the international state-of-the-art the standard interface I++/DME has been chosen. This interface emerged in 2000. In allows not only dimensional inspections with tactile sensors than also with optical sensors. Thereby the I++/DME standard integrates the novel OSIS interface. The I++/DME interface [27] is an open neutral interface which encapsulates the expertise of the manufacturer of the measuring machine. At the same time due to the international standardisation efforts [28] it enables the maximum interoperability in terms of docking to offline programming and analysis software.

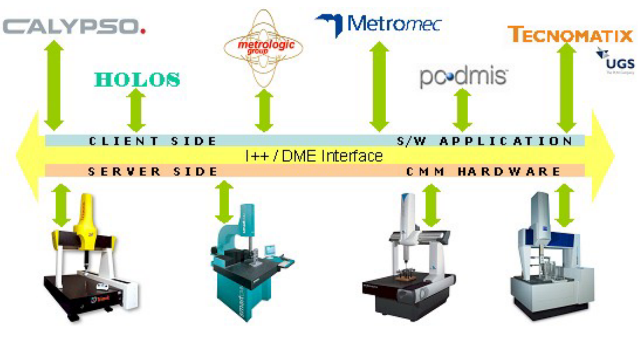


**Fig. 4: Interoperability test of the I++ DME interface**
[Source: http://iacmm.org/50862595e2110f906/index.html]

The progress and fast increasing establishment of the I++/DME interface can be judged from the interoperability tests (Fig. 4) which have been demonstrated in April 2005 at the Fair „Control" in Sinsheim, Germany. The tests were performed by the international association of CMM manufacturers (ia.cmm, Europe) with support from the National Institute of Standards and Technology (NIST, USA) and from the Automotive Industry Action Group (AIAG, USA).

Thereby each of the five different CMMs has been operated via the I++/DME interface with six different software packages (Fig. 4) for offline programming (OPS). The CMMs were from Hexagon Metrology SpA (Italy), Renishaw plc (UK), Trimek Metrologica Engineering (Spain), Wenzel Präzision GmbH (Germany) and from Carl Zeiss Industrielle Messtechnik GmbH (Germany).

## 5. CASCADED MULTISENSOR SYSTEMS

Due to the nature of micro- and nanostructured components dimensional inspections require the deployment of more than one sensor respectively sensor principle. The combination of sensors with very different measuring range and very different measuring resolution is typical for measuring objects which shall be inspected with nano measuring machines [29]. In order to enable the automatic execution of inspection plans for micro- and nanostructured components the measuring machine must include a cascaded multisensor system.

### *5.1. Setup and Working Principle*

A cascaded multisensor system consists of multiple probing sensors with very different measuring range and very different measuring resolution (Fig. 5). It is characterised by the internal information processing between the different sensors. It enables the stage to stage accuracy-dependent inspection of micro- and nanoscale three dimensional features. That specifics must be taken into account at inspection planning and at the execution of inspection plans. There is a need for novel, multi-stage inspection strategies.

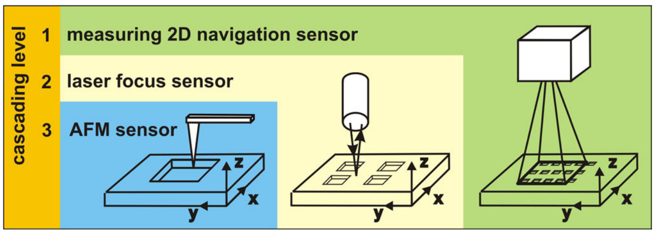


**Fig. 5: Setup of a cascaded multisensor system**

From the viewpoint of the I++/DME client respectively the OPS, the cascaded multisensor system must act as one sensor with multiple features. Consequently this structure incorporates the fusion of the data of the different sensors in order to estimate the measured inspection feature. Basically similar concepts are already known from measurements in the macroscopic scale [30]. Nevertheless up to now there are no solutions known that are capable of measuring automatically geometrical primitives in the micro- and nanoscale with multiple sensors supplementing each other.

Each sub-sensor of a cascaded multisensor system must be adaptive and intelligent. Thereby the term intelligent refers to the ability to communicate with other sub-sensors and to monitor its status autonomously. The term adaptive refers to the ability to adapt its parameters for example gain, illumination, applied analysis algorithm to the current measuring conditions.

These two properties are critical for the automatic execution of inspection plans. The execution must not terminate:

- if a difference between the expected shape (CAD data) and the actual shape of an inspection feature occurs.
- if the measuring conditions change during the measuring process e.g. change of illumination from the environment.

Typical sensors for deployment at nano measuring machines are for example AFM sensor, laser focus sensor as well as a area-wise working navigation sensor (CCD camera with variable magnification, i. e. zoom lens).

The navigation sensor should provide µm-resolution whereas the other two mentioned sensors provide nm-resolution. The navigation sensor is utilised for the µm-precise rough navigation. A similar concept is used in [31]. Furthermore in [32] a novel system-theoretical model of an intelligent, adaptive sensor as part of the process chain is introduced. Each sub-sensor of the cascaded multisensor system can be described by the system-theoretical model.

### *5.2. Calibration of Cascaded Multisensor Systems*

In order to execute inspection plans automatically all sensors of the cascaded multisensor system must be calibrated. After each individual sensor has been calibrated, all sensors must be calibrated to each other. Basically the goal of the second calibration step is to determine precisely the three dimensional distance between the origins of the different sensor coordinate systems. Typically each sensor has its own coordinate system. The origin of the sensor coordinate system (SCS) of a tactile probe is usually situated in the centre of its probing element e.g. probing ball. Exemplarily the SCS for an AFM sensor is situated at its tip. In contrast the origin of the SCS of an imaging sensor e.g. CCD sensor is usually laterally in the centre of the field of view and vertically in the sharpness level.

The calibration of the sensors to each other poses the inherent problem of calibration targets. The calibration targets must be suitable for accurate measurements with all sensors of the cascaded multisensor system. As cascaded sensor systems span several magnitudes of size and due to the different physical working principles of its sensors, suitable calibration targets are currently investigated. Only after achieving a sufficient calibration of the sensors to each other, inspection strategies harnessing the capabilities of the cascaded multisensor system will become available.

## 6. EXPERIMENTAL RESULTS

The proposed closed process chain for dimensional measurements of micro and nanostructured components as shown in Fig. 3 has been set up at the TU Ilmenau. Its operability has been demonstrated several times for example in May 2004 at the public Status Colloquium of the collaborative research centre (SFB 622) in Ilmenau, Germany. Thereby the execution of an inspection plan for a microstructured component with one probing sensor has been demonstrated. The laptop with the OPS was in the lecture hall (“Senatssaal”) whereas the NMM was in an other building (“ZMN”). Additionally a connection to a web camera installed at the NMM had been established in order to show the movement of the measuring machine.

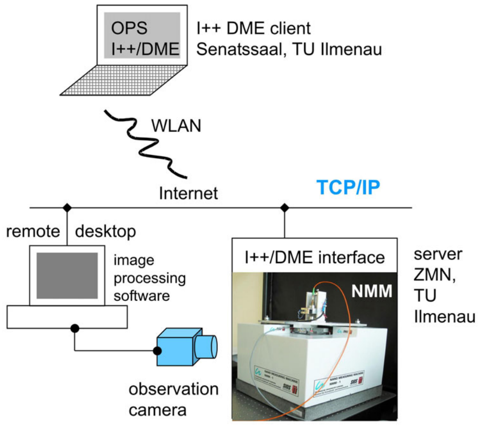


**Fig. 6: Experimental setup for the demonstration of the remote execution of a inspection plan via the I++/DME interface [21]**

In the same year in June a similar setup has been chosen to execute an inspection plan via I++/DME interface from a laptop situated in Sankt Petersburg, Russia (GSM connection via handy to the Internet) on the measuring machine situated in Ilmenau, Germany (Fig. 6). This demonstration has been performed during the 10th IMEKO TC7 International Symposium on Advances of Measurement Science 30.06.-02.07.2004 in Sankt Petersburg, Russia.

Automatic dimensional inspections with multisensor systems via the I++ DME interface have been performed for macroscopic features. Due to the ongoing investigation of the calibration of cascaded multisensor systems similar to Fig. 5, automatic dimensional inspections with a cascaded multisensor system have not been performed yet.

## 7. CONCLUSION

Cascaded multisensor systems at micro- or nanomeasuring machines, which are incorporated into closed quality loops, will significantly extend the capabilities for automated dimensional inspections of micro- and nanostructured components. Future research will deal with theoretical fundamentals of cascaded multisensor systems including multistage inspection strategies. In parallel experimental investigations will be executed. Currently the calibration of cascaded multisensor systems is investigated.

The expected benefit will be the availability of automatically performed in-situ measurements of three dimensional features of micro- and nanostructured components in the near future. Thereby typical fields of application are measurements on wafer level before further assembly, measurements at injection moulded micro- and nanostructured components as well as measurements at micro- and nanostructured components manufactured on ultra precision manufacturing machines. This will have a significant economic impact in terms of cost reduction and rise of production efficiency.

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