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50. Internationales Wissenschaftliches Kolloquium
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S. Töpfer / G. Linß / U. Nehse

Prerequisites for Automatic Execution of Inspection Plans for Dimensional Control of Micro- and Nanostructured Components

ABSTRACT

Due to the fast advancement of manufacturing technologies for micro- and nanostructured components [1], [2] 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 the dimensional control 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 multi sensor system consisting of adaptive, intelligent sensors with cascaded measuring ranges. The paper provides a novel and consistent overall picture 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 [3] which must overcome the limitations of research oriented nanometrology.

INTRODUCTION

Recently a study on the international state-of-the-art in the field of micro-production technologies has been carried out [4]. 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 [5], [6]. State-of-the-art are functional test which are usually executed after the assembly of the whole micromechanical product [7], [8]. Approximately 80 percent of the value creation occur after the wafer level [9]. 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 [7]. 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 [7], "3D-Mikro" 2005-2007 [10], "3D-µMess" 2005-2007 [11] and „ParTest" 2005-2007 [9]. 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 id est 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.

INSPECTION PLANNING

The term inspection planning is defined in the VDI/VDE/DGQ guideline 2619 [12]. Regarding the overall system described in this paper two aspects of inspection planning should be differed. 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 [8],
- 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 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.

CONDITIONS FOR DIMENSIONAL INSPECTIONS

This paper focuses on dimensional inspection of micro- and nanostructured components. This is very important for inspections on wafer level. Thereby predominantly micro mechanical products and all other products where geometry and size of structures are suitable to evaluate their functionality are inspected. 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 [13], [14]. This is a challenging task. Moreover the critical dimension is constantly decreasing. Exemplary the International Technology Roadmap for Semiconductor (ITRS) [15] 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.

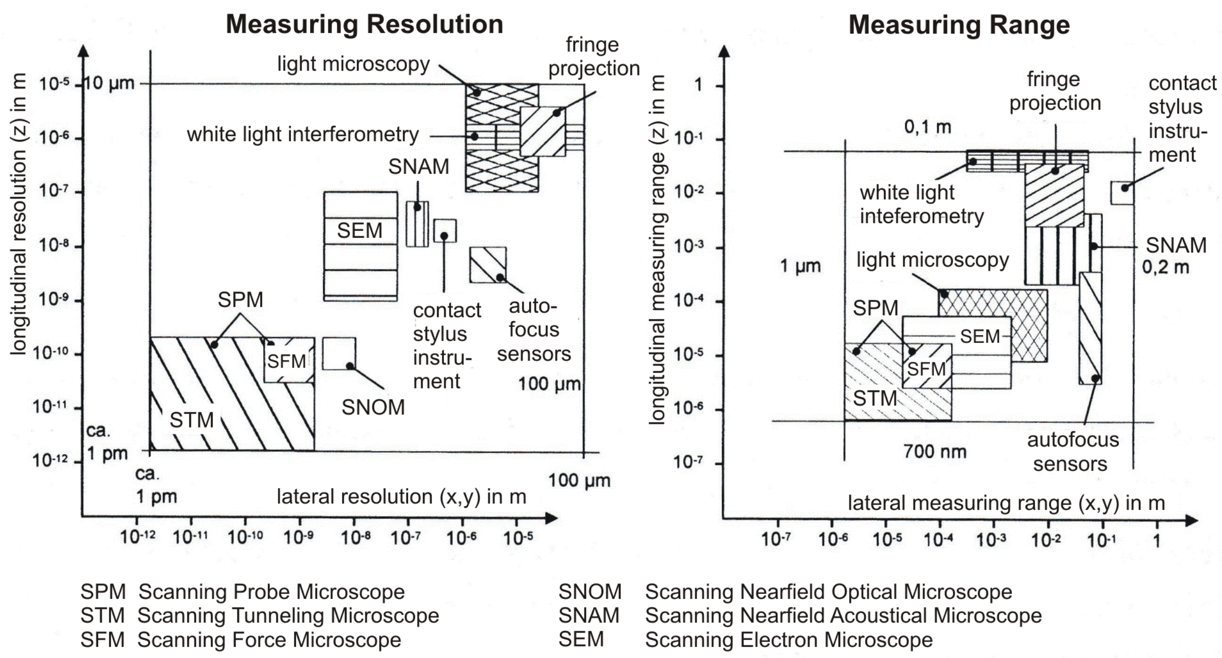

Fig. 1: Resolution and measuring range of typical measuring methods for micro- and nanoscale components [16]

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 by factor 2 whereas the volume decreases with factor 3 [16].

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 [17], [18]. Otherwise wrong measuring results will be attained.

An 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. 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 [19].

During the last ten years tolerance systems, measuring strategies and parameters for describing the properties of micro systems did not change essentially [16]. 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 [13]. 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 as last issue the fixing of the measuring object without introducing stress has to be listed. Bader [20] indicates freeze clamping, rheological fluidic fixing, needle fixing cushion and electrostatics as possible methods.

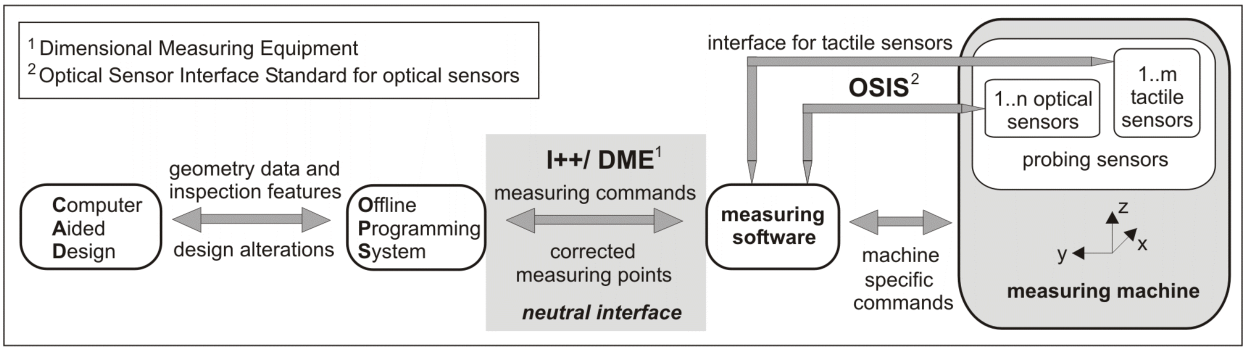

Fig. 2: General setup of a small closed quality loop for 3D dimensional measurements with coordinate measuring machines

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 [21]. 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. Its principle setup is depicted in Fig. 2. This principle applies not only for measurements in the macroscopic scale but also for measurements in the micro- and nanoscale. In [22] a detailed description of the application of this principle for inspecting micro- and nanoscale features is given.

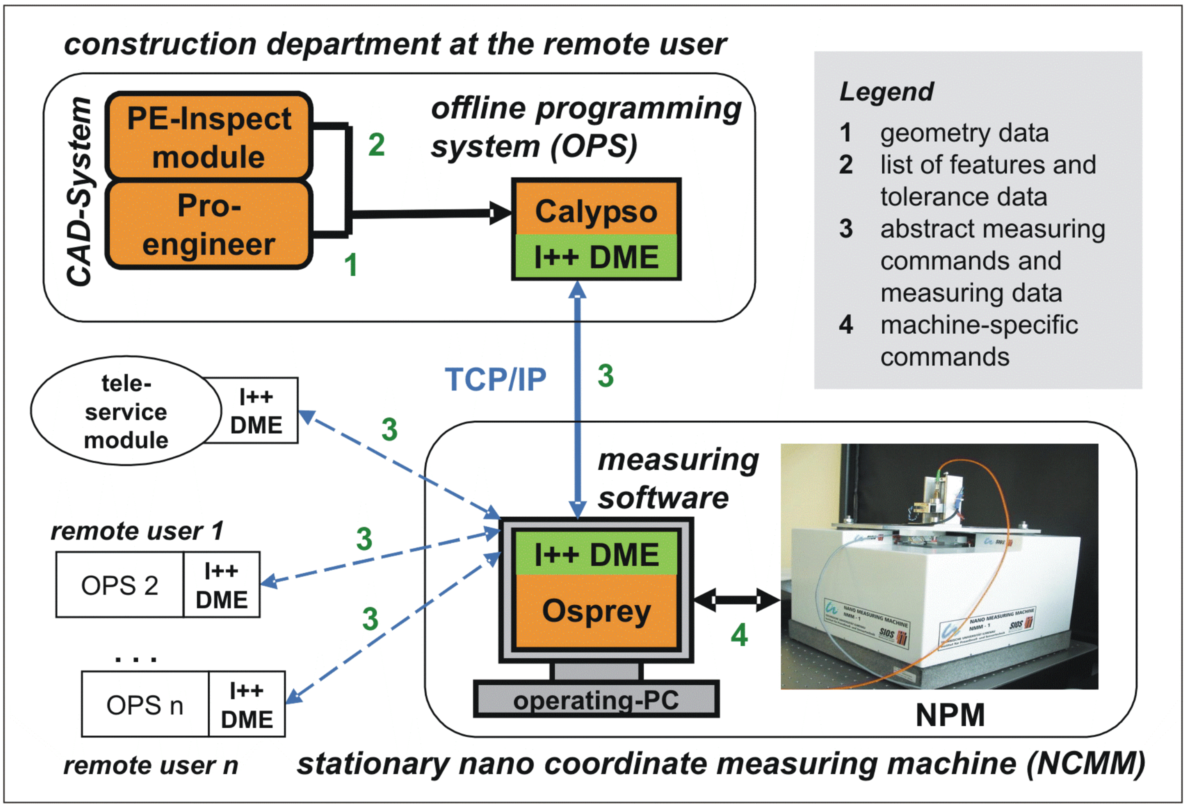

Fig. 3: Closed process chain for dimensional measurements of micro- and nanostructured components utilising the nano positioning and nano measuring machine (NPM)

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 (NPM) [23] (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 [24]. Consequently it allows to initiate the automatic execution of the inspection plan. Thereby the OPS and the measuring software are communicating bidirectional 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 NPM. These commands are directly executed by the NPM. 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 adaptation of manufacturing processes is initiated.

As Fig. 2 illustrates 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 a lot of 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 [25]. 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 [26].

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) [27] 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 the dimensional inspection of features with tactile sensors than also with optical sensors. Thereby the I++/DME standard integrates the novel OSIS interface. The I++/DME interface [28] is an open neutral interface which encapsulates the expertise of the manufacturer of the measuring machine outwards. At the same time due to the international standardisation efforts [29] it enables the maximum interoperability in terms of docking to offline programming and analysis software.

The progress and fast increasing establishment of the I++/DME interface can be judged from the interoperability tests which have been demonstrated in April 2005 at the Fair „Control“ in Sinsheim, Germany. With support from the National Institute of Standards and Technology (NIST, USA) and from the Automotive Industry Action Group (AIAG, USA) the international association of coordinate measuring machine manufacturers (ia.cmm, Europe) demonstrated the interoperability of the I++/DME interface. Thereby five different measuring machines have been operated via the I++/DME interface indifferently with one of six different software packages for offline programming (OPS). The measuring machines 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). The deployed OPS were Calypso, Holos, Metrolog XG, Metrosoft CM, PCDMIS and eM-Measure (Tecnomatix).

CASCADED MULTI SENSOR SYSTEM

Due to the nature of micro- and nanostructured components the dimensional inspection requires 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 [30]. In order to enable the automatic execution of inspection plans for micro- and nanostructured components the measuring machine must include a cascaded multi sensor system.

A cascaded multi sensor system consists of multiple probing sensors with very different measuring range and very different measuring resolution. It is characterised by the internal information processing between the different sensors and it enables the stage to stage accuracy-dependent inspection of micro- and nanoscale 3D dimensional features. That specifics must be taken into account at the inspection planning and at the execution of inspection plans. There is a need for novel, multi-stage inspection strategies.

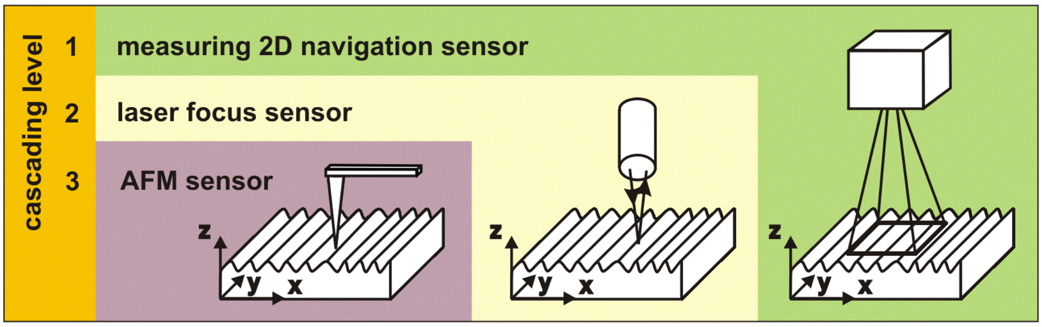

Fig. 4: Setup of a cascaded multi sensor system

From the viewpoint of the I++/DME client respectively the OPS the cascaded multi sensor 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 [31]. 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. Fig. 4 illustrates the setup of a cascaded multi sensor system. Each sub-sensor 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 of the inspection plan must not terminate:

- if a difference between the expected shape (CAD data) and the actual shape of an inspection feature occurs e.g. defects.
- if the measuring conditions change during the measuring process e.g. change of the 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 id est zoom lens). The navigation sensor should provide sub-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 [32]. Furthermore in [33] a novel system-theoretical model of an intelligent, adaptive sensor as part of the process chain is introduced. Each sub-sensor of the cascaded multi sensor system can be described by the system-theoretical model.

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 Technische Universität Ilmenau. Its operability has been demonstrated several times for example in May 2004 at the public Status Colloquium of the collaborative research centre (SFB622) in Ilmenau, Germany. Thereby the execution of an inspection plan for a microstructured component has been demonstrated. The laptop with the OPS was in the lecture hall ("Senatssaal") whereas the NPM was in an other building ("ZMN"). Additionally a connection to a web camera installed at the NPM had been established in order to show the movement of the measuring machine.

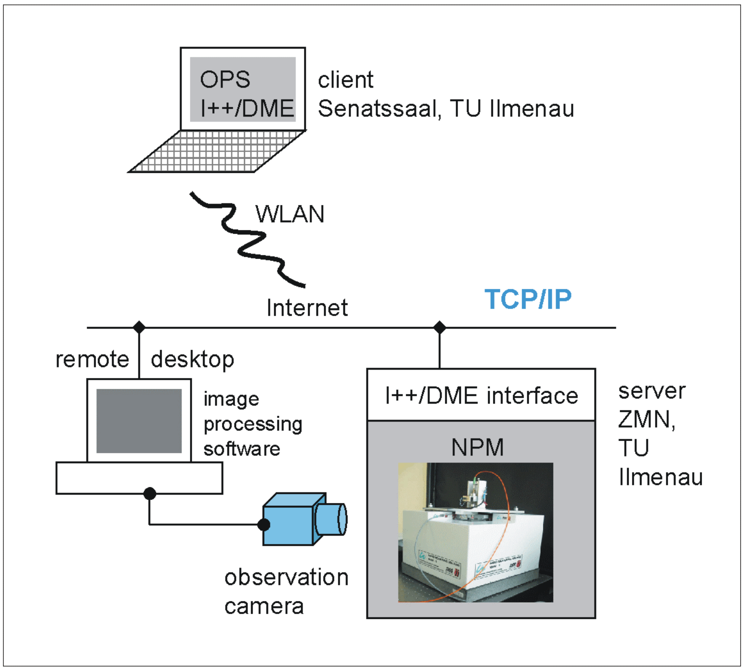

Fig. 4: Experimental setup for the demonstration of the remote execution of a inspection plan via the I++/DME interface

In the same year in June a similar setup has been chosen to executed 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. This demonstration has been performed as part of a presentation held at the 10th IMEKO TC7 International Symposium on Advances of Meas-urement Science 30.06.-02.07.2004 in Sankt Petersburg, Russia.

CONCLUSION

A comprehensive description of the state-of-the-art and of the challenges for dimensional inspection of micro- and nanostructured components has been laid out. The small closed quality loop has been presented as a decisive step towards automatic execution of inspection plans. The significance of the paper lies with the extension of the capabilities for automated inspection planning and inspection plan execution for micro- and nanostructured components.

The concept of cascaded multi sensor systems has been explained. Future research will deal with theoretical fundamentals as well as with the experimental setup of cascaded multi sensor systems for dimensional inspection of micro- and nanostructured components. The expected benefit will be the availability of automatically performed in-situ measurements of 3D 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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