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HARD- AND SOFTWARE INTERFACES ENABLING EFFICIENT INSPECTION PLANNING AT THE NANO POSITIONING AND NANO MEASURING MACHINE (NPM)

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Abstract – The large number of inspection features at dimensional measurements in the nano range entails a need for a lossless information flow along the process chain. Within the frame of fundamental research the concept of the closed process chain is adapted to the utilization at the NPM. Thereby, novel principles of knowledge distribution and novel inspection strategies are investigated. The latter focuses on the goal-oriented combination of overlapping measuring ranges of different scale of different sensors. In this regard the required sensor adaptability is also analysed. The paper deals with the hard- and software interfaces necessary to realize the closed process chain philosophy at the NPM. As external, neutral open interface the I++/DME (dimensional measuring equipment) interface is used. It supports the widespread and flexible use of the NPM for local as well as for remote operators. Furthermore, it provides the direct link to standard analysis and offline programming software and thus indirectly to CAD software. The presented research enables the efficient inspection planning and its automatic execution at the NPM. This approach drives the metamorphosis of the NPM from a scientific research machine towards a nano coordinate measuring machine interesting to other research areas and to industry.

Keywords: inspection planning, adaptive sensors, neutral open interface

1. INTRODUCTION

The state of the art comprises the novel concept of the closed process chain for the macro range. This concept has been developed within the WEPROM project [1]. Thereby the redundant entering of data along the process chain has been eliminated. The novel concept does not contain system breaches. The construction data and the inspection features [2] are imported into an off-line programming system for measurements (OPS). Afterwards the inspection plan is created and sent to the measuring machine where it is executed.

Until now, this concept has not been investigated regarding its applicability in the nano range. The NPM developed at the Technical University Ilmenau is currently a highly innovative tool for experimenters and scientific institutions (Fig. 1) [3].

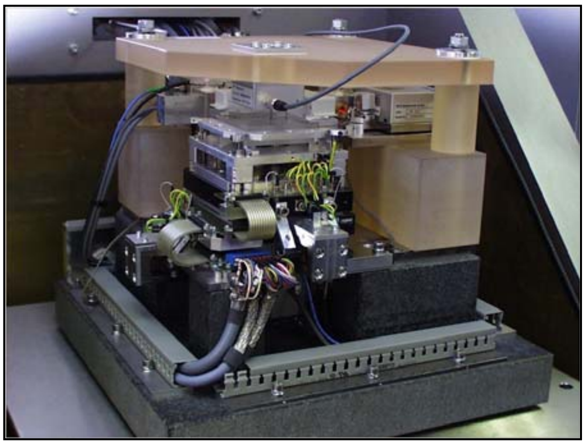

Fig. 1. Mechanical structure of the NPM [3]

However, it lacks an external standard interface to perform CAD data based, automatic measurements with subsequent analysis of the measuring results. Compared to measurements in the macro range with less than 10 features the number of inspection features is increased by factor 10^5 for measurements in the nano range with up to 300000 features. The large data amount that occurs at all process levels such as design, manufacturing and quality control drives the need for a lossless information flow and for automated measurements. Thus, the objective of the presented research is to enable the NPM to automatically execute inspection plans for features in the nano range. The paper deals with fundamental research regarding the methods and principles necessary to achieve this objective.

The paper tackles the issue to apply the concept of the closed process chain to the NPM in chapter two. Thereafter the external standard interface and the entailed knowledge distribution are considered. The next chapter deals with the inspection strategy whereby a method to overcome the gap between the macro and the nano range is proposed. After considering the sensor adaptivity the achieved results are detailed in chapter six. Finally some concluding remarks are made and a prospect of future research activities is outlined.

2. CLOSED PROCESS CHAIN AT THE NPM

A comprehensive literature, online and patent research has been executed to determine the state of the art. Focus of the study was on the process chain itself and on the content of the existing CAD data formats and special data formats for microstructures (Table I). Thereafter, a concept for an efficient inspection planning [4] at the NPM has been developed. The term inspection planning within the context of this paper comprises not only the planning process itself than also the execution of the inspection plan.

TABLE I. Comparison of different data formats for microstructures (Caltech Intermediate Form (CIF), Electronic Data Interchange Format (EDIF), Open DataBase (ODB++))

Information		**CIF**	**EDIF**	**GDS II**	**Gerber**	**STEP AP210**	**ODB++**
Compression		-	/	/	-	+	+[1]
Standard/ manufacturer		(a)	(b)	(c)	(d)	(e)	(f)
Tolerance data		-	/	-	-	+	+
Def. of symbols		+[2]	+	+	-	+[3]	+
Data type	ASCII	+	+		+	+	+
	binary			+			
Description	*hierachic*	+	+	+	+	+	+
	linear						

[1] optional [2] limited [3] pre-defined

(a) Hochschulgemeinschaft **(b)** Motorola, Texas Instruments **(c)** Calma **(d)** Gerber **(e)** ISO standard 10303 **(f)** Valor

+ fulfilled **/** no data **–** not fulfilled

The search has shown that currently only the data formats STEP (Standard for the Exchange of Product Model Data) and ODB++ match the geometry data with the associated tolerance data of the individual features. However, ODB++ is not wide spread and the STEP format is differently implemented regarding the scope of the implementation and the used application protocol [5]. Thus, the solution to use an additional module for the deployed CAD software is necessary. This module enables the retrieval of a list of inspection features and the associated tolerance information. An alternative to the combination of the CAD software Proengineer and the module PE-Inspect is Unigraphics with the module UG-Inspect.

Fig. 2 illustrates the process chain at the NPM. The closed process chain starts with the design of 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). The OPS is used to perform the inspection planning. The thereby created measuring sequence is transmitted via the I++/DME interface to the NPM. There the I++/DME commands are interpreted as machine-specific commands. These commands are directly executed by the NPM.

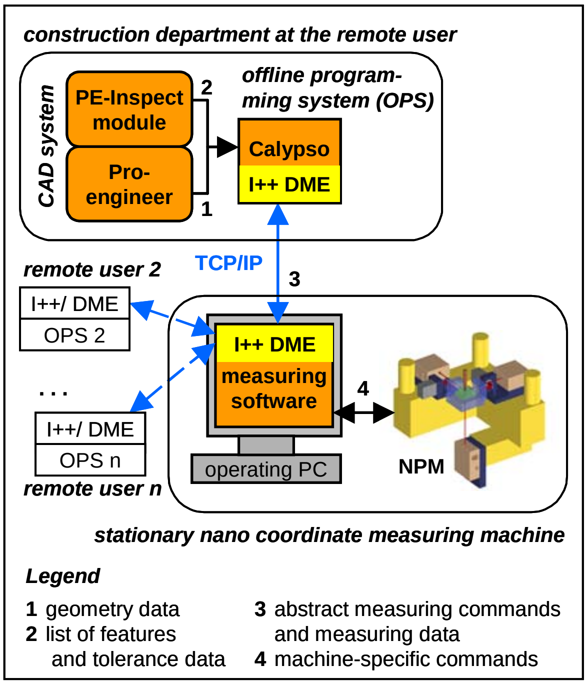

Fig. 2. Closed process chain and interfaces at the NPM

The measuring points are sent back to the OPS which works also as analysis software. Thus, a dimensional analysis of the delivered point cloud is performed.

2.1. Limitations of the deployed CAD-System

The deployed CAD system Proengineer does limit the design of parts with dimensions in the millimetre and nanometer range. On the one hand the software supports the definition of the unit nm. On the other hand the model accuracy limits the relation between the largest and the smallest dimension of the designed part. At maximum it amounts to 0.0001. Exemplarily, if designing a part with side length of 100 mm the smallest size, which can be defined, amounts to 0.00087 mm. However, with regard to the described limitation the CAD system is still suitable for designing part geometries within the nanometer and micrometer range. The quoted numbers have been determined through experiments with the Proengineer version from 2001.

3. THE I++/DME INTERFACE

The International Association of Coordinate Measuring Machine Manufacturers IA.CMM supports the neutral I++/DME interface [6]. Compared to DMIS (Dimensional Measuring Interface Standard) the I++/DME interface is situated at a lower level in the technical interface hierarchy. DMIS has not met the expectations in terms of providing a standard interface with the connected compatibility [7]. Creating a DMIS program for one measuring machine does not necessarily mean the program can be executed by another measuring machine with a DMIS interface.

I++/DME interface standard has been initiated mainly in order to overcome the compatibility issue. The founders of the I++ group namely Audi, BMW, DaimlerChrysler, Volkswagen, and Volvo specified in 2001 a list of requirements, which they wanted to be realized. The European coordinate measuring machine (CMM) manufacturers responded and jointly worked out the current version 1.4 of the I++/DME standard. The company Carl Zeiss had had equipped their CMMs with this interface already in May 2003 [8]. However, many CMM manufacturers are still working to make their CMMs I++/DME compliant. Similarly manufacturers of OPSs are doing the same.

3.1. Functional scope of the I++/DME interface

The I++/DME interface is based on a client-server concept. The CMM is equipped with the I++/DME server whereas the client is implemented in the offline programming system or similar software. The interoperability of CMMs is supported through this setup.

The main idea is that the client respectively the OPS first asks the CMM which tools are available. Secondly the client asks exemplarily whether tool 1 is able to measure a specific feature for example to scan a circle. If the tool provides the desired function the command to measure the feature is sent by the client. Physically the communication is executed via TCP/IP [9]. The I++/DME interface is not only suitable for tactile than also for optical sensors [10]. Regarding the latter ones DMIS has never been sufficient because its focus was on tactile sensors. The I++/DME interface does support optical sensors via the Optical Sensor Interface Standard (OSIS) [11]. This interface is also supported by the IA.CMM [6]. It shall incorporate a compulsory standard for the integration of optical sensors and CMMs. Additionally it is expected to improve the comparability of optical sensors through standard criteria for sensor specification [12].

3.2. Novel quality of knowledge distribution

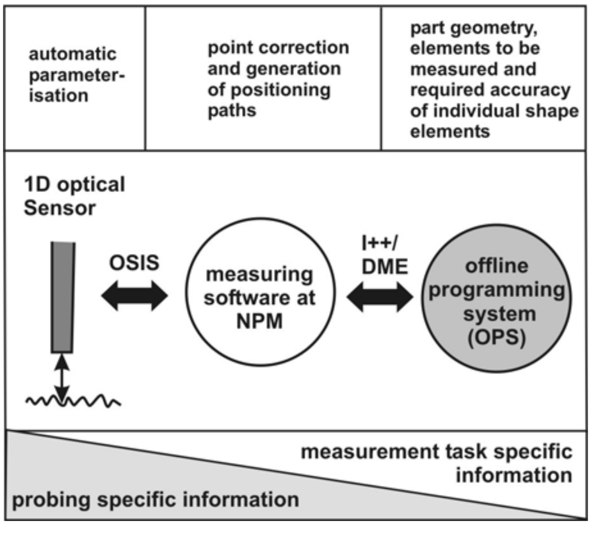

Fig. 3. Knowledge distribution along the process chain

The previously described interface concept does influence the knowledge distribution [13] and task allocation. Basically, both interfaces OSIS and I++/DME encapsulate the specific knowledge of the manufacturer of the optical sensor or of the CMM. The novel approach is to deliver the requirements such as which feature shall be measured at which position at which accuracy level. The sensor must parameterise itself. It must adapt to the existing measuring conditions for example background illumination, surface structure of the measuring object etc.. Due to the required probing uncertainty the sensor adjusts its resolution, measuring mode and measuring speed automatically. This entails a different knowledge distribution. As Fig. 3 shows the amount of data regarding the probing process is at maximum at the sensor level and decreases to the right whereas the amount of data concerning the measuring task has its maximum at the OPS. Hence, the process chain contributes to the need for intelligent, adaptive sensors.

4. INSPECTION STRATEGY

As initially stated the NPM does required methods to overcome the gap between the macro and the nano range. This is due to its nature. The current NPM has a measuring volume of 25 mm x 25 mm x 5 mm. It has a resolution within its measuring axes x,y and z of 0.1 nm [3]. There are two available machine configurations. At the first measurements within the nanometer range are taken with an AFM sensor, which is integrated into the NPM. At the second a laser focus sensor attached to the Zerodur plate at the top of the NPM is used for probing along the z-axis with nanometer resolution. Additionally a CCD camera is attached to NPM using partially the same optical path as the laser sensor. It is deployed for lateral measurements. A decisive advantage of an optical sensor with nanometer resolution compared to a tactile sensor with similar resolution is that no direct contact between the sensor and the measuring object is required. Consequently, the optical sensor does not influence or alter the measuring object. This condition is not necessarily met when the measurement is tactilely executed.

The new quality lies within the different types of sensors, which are necessary for the inspection planning at the NPM. They are deployed in order to bridge the gap between the macro and the nano range. Thus, an unique requirement of the NPM is the large difference between the measuring ranges of the applied sensors. The inspection planning must be adapted to this specific requirement. A suitable inspection strategy should be similar to the zoom process at optical measurements where a printed circuit board is first inspected with a small magnification and afterwards with a high magnification to measure single solder bumps. The calibration of the macro and the nano sensor to each other is a critical issue for the following inspection strategy. It is important that data exchanged between the sensors are supplemented with the uncertainty which is achieved by the individual sensor. Another important issue is the utilization of a safety region concept in order to prevent collisions between the sensor and the measuring object. This concept is already avaliable through the OPS. Nevertheless, the applicability of this concept must be directly tested at the NPM with the described sensor configuration.

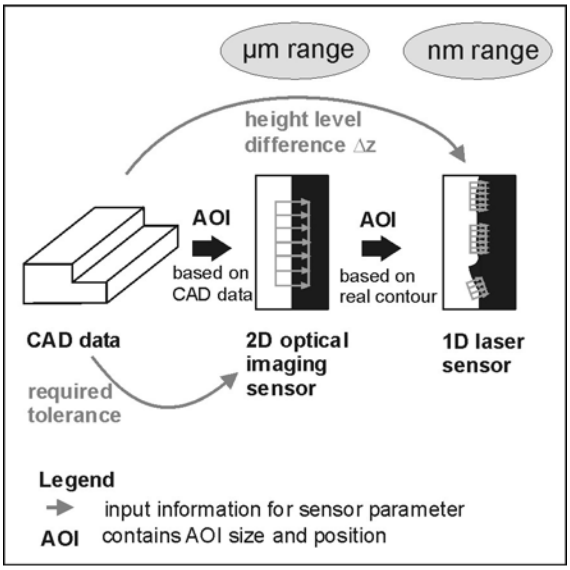

Fig. 4. Information flow necessary to bridge the gap between macro and nano range

Different from [14] Fig. 4 shows a new principle to affiliate the capabilities of a sensor with nanometer resolution and a macro sensor with µm resolution. An optical 2D imaging sensor is applied in order to provide the functionality to navigate on the measuring object within the macro respectively µm range. Thereby, the location and size of the area of interest for the CCD sensor are derived from the CAD data. As result of this measurement the real contour is known at µm resolution. In the next step the areas, which shall be measured with nanometer accuracy, are derived from the real macro contour. Afterwards the target structure respectively area of the object can be probed with a nano sensor e.g. AFM or focus sensor. This methodology allows harnessing knowledge about the macroscopic structure of the measuring object as input for the nano sensor. Exemplarily the sensor parameters of the nano sensor are adjusted not only based on data from the CAD model e.g. difference in height levels than also based on data from the navigation sensor e.g. measuring point distance.

5. SENSOR ADAPTABILITY

Another decisive issue is the large number of parameters of 2D optical sensors or nano sensors in comparison to tactile sensors. The handling of these parameters must be taken account of in order to perform a successful inspection planning.

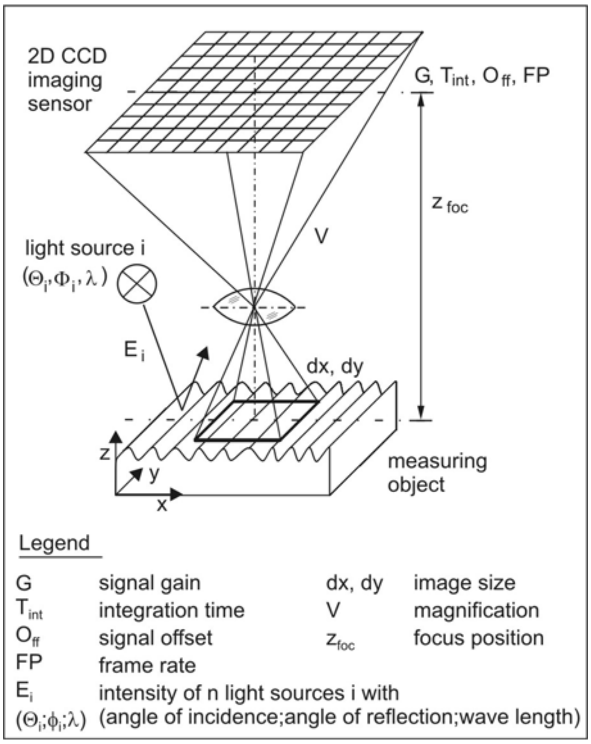

Fig. 5. Characteristic parameters of a 2D imaging sensor

The resume of chapter 3 is that due to the knowledge distribution, which is inherently to the process chain, intelligent, adaptive sensors are needed. A third argument for this viewpoint beside the number of sensor parameters is the large number of inspection features when performing measurements in the nano range. Additionally, [15] illustrates the need for operator-independent measurement results. If the prerequisite in terms of the availability of intelligent, adaptive sensor is not fulfilled automatic execution of an inspection plan is not possible. Fig. 5 illustrates the parameters that are to be adjusted when measurements are taken with a CCD camera.

Basically an overall closed loop control in order to achieve an automatic parameterisation of a CCD sensor or of any other sensor is needed. The state of the art is still that partially single steps of the closed loop control are executed automatically e.g. automatic gain adjustment or automatic adjustment of the illumination [16] or auto focusing procedures. However, until now no overall method has been investigated in detail.

6. EXPERIMENTAL RESULTS

First measurements have been performed with the nano measuring machine (NPM) with the following sensor combination. On top of the Zerodur machine frame a laser focus sensor has been installed. The sensor has a height measuring range of 10 µm and a spot diameter of 1 µm. The resolution of the zero crossing of the sensor in z-direction amounts to <1 nm [17]. The described measuring setup enables highly precise measurements in vertical direction.

Additionally a high resolution CCD camera (1000 x 1000 square pixels with 7,4 µm side length) suitable for optical precision measurements has been installed on the NPM. The magnification amounts to 24. Thus, the area of the object which is pictured by the camera is 302.8 µm x 302.8 µm. Through the utilization of a beam splitter the camera uses partially the same optical path as the laser focus sensor (Fig. 6). Moreover the light of an external light source is induced via a second beam splitter. Thus, the surface of the measuring object is illuminated. This setup enables the goal-oriented navigation of the focus sensor. The first measurements have shown that the chosen sensor combination enables efficient measurements. The ability to bridge the gap between the nano range and the macro range is attained.

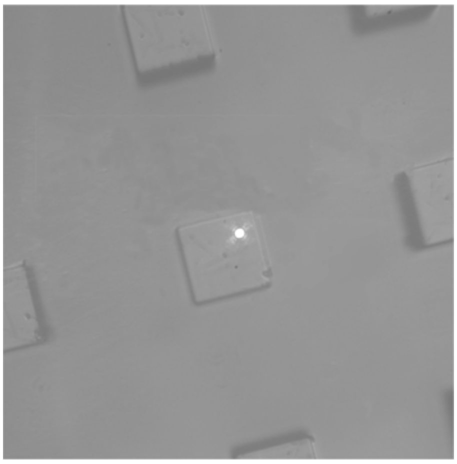

Fig. 6. Image of a measuring scene taken with a high resolution CCD camera at the nano positioning and nano measuring machine showing the spot of the laser focus sensor at the top level of 50 µm square bumps

Due to the ongoing work to install the CCD camera and the focus sensor as well as the necessary software at the NPM no inspection plan has been executed via I++/DME so far. Despite this fact, the process chain itself has been successfully tested at a classical coordinate measuring machine.

The CAD model of a ring gauge has been created with ProEngineer. Afterwards the list of inspection features has been extracted. The CAD data and the feature list have been imported into the offline programming system (OPS). Thereafter an inspection plan for the ring gauge, which had been created with the OPS, has been automatically executed via the I++/DME interface. Due to the current lack of fully adaptive and intelligent sensors the sensor parameters had been adjusted manually before the execution of the inspection plan. The inspection plan did use not only a CCD camera than also a tactile probe.

Initially, the execution of the inspection plan via the I++/DME interface was started within one laboratory. Afterwards, the remote capabilities of I++/DME have been validated through the execution of the inspection plan via the I++/DME interface from other locations than the laboratory with the CMM. Thereby a web cam was utilised to send pictures of the current condition of the CMM to the remote user controlling the CMM via the OPS.

The conducted tests have shown that I++/DME interface is able to handle dimensional measures from the mm to the nm range. In [10] the length unit is defined as mm but no restriction regarding the resolution below this increment is specified. This means that the I++/DME interface can handle nm if it is implemented accordingly. Furthermore the tests proved that the OPS can handle only data equal to or larger than 1 µm. Thus, a converter is necessary to convert the data from the NPM from nm to µm. This enables the comparison of the measured structure with its CAD data within the OPS. However, this means also that the actual CAD model of the nano structured component must be converted into the µm range as well.

7. CONCLUSION

As result of the research a concept for a closed process chain at the NPM has been developed. Thus, the basic conditions for an automated execution of inspection plans for dimensional measurements within the nano range have been achieved. Applying the latest technology regarding external interfaces to the NPM enables its widespread and remote use. The type of software the remote user applies for its inspection planning is no longer a restriction in terms of compatibility to the NPM. This approach drives the metamorphosis of the NPM from a scientific research machine towards a nano coordinate measuring machine interesting to the industry. Furthermore fundamental research regarding the methods and principles, which are necessary to apply the concept of the closed process chain at the NPM, has been executed. The paper proposes how the distribution of knowledge within highly complex measuring systems will develop. Moreover an inspection strategy exploiting the different measuring range of a macro and a nano sensor is presented.

Further research will aim to identify and eliminate the weaknesses of the developed concept regarding the specific conditions for dimensional measurements within the nano range. A major research field will focus on adaptive sensors, which are crucial for the automatic execution of inspection plans. A critical issue, which will be solved in the near future, is the highly accurate calibration to each other of the navigation sensor and the nano sensor at the NPM. Thereby, the different resolution of both sensors determines the residual uncertainty after the calibration. The influence of the residual uncertainty on the inspection strategy will be investigated.

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