Traceable measurements using machine tools

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Abstract

Flexible manufacturing processes for high quality products at low costs are one of the main research objectives in the field of production technology.
The quality check inspection of large or complex work pieces manufactured on machine tools often takes place beside the production line. The manufacturing process is interrupted and transportation, handling and the loss of the original manufacturing setup influences the work piece quality. To assure the traceability of the quality check inspection the quality features are measured on a CMM. The high invest for a CMM and the mentioned aspects show the need for a machine integrated traceable measuring process for product's quality assurance.

Almost every new machine tool is equipped with a probing system for the measurement of simple geometric features. These operating tactile touch probes shall provide the possibility of testing product characteristics right after the manufacturing process. Especially the rejection rate in processes with a high degree of added values or small numbers of quantities should be lowered significantly. Because of the process-oriented solution, the work piece would not have to be removed from the machine tool. The work piece quality could be improved.
Nevertheless, due to disturbances like machine defects or temperature fluctuations, a retraceable measurement process is not possible. The measurement data are not comparable and cannot be used for a process improvement or regulation control.
New approaches at the WZL are aiming to assure a traceability of the measuring inspection processes on machine tools. The fusion of appropriate methods for the traceability of CMM's and innovative calibration methods for machine tools (simultaneous Multilateration with 4 Laser Tracking Interferometers) will allow the determination of a measurement uncertainty for the measurement system "touch probe and machine tool".

In the field of Coordinate Metrology the measurement uncertainty can be determined by

- Experiments (DIN ISO 15530-3, VDI 2617-8)
- Uncertainty budget (VDI 2617-11)
- Numerical Simulation (DIN ISO 15530-4, VDI 2617-7).

The different methods have to be adapted, further developed and validated for the capability for machine tools.

Within the research activities a guideline has been developed that will allow the implementation of a traceable measurement process on the machine tool.

1 Motivation

The measurement of large-scale devices is absolute vital for the manufacturing and alignment of many products which modern life depends on. Large Volume Metrology (LVM) is concerned with the measurement techniques and methods for structures, objects and assemblies of a few meters up to tens of meters. These techniques are necessary because the items demand special requirements for the measurement process and the quality control. Structures or objects are too large to fit into conventional measuring machines or to be transported to a calibration laboratory. They have to be measured *in process* or *in situ*. The trade off between increasing work piece dimensions and constant or even decreasing tolerances (for example in the field of large gears for wind power industries) and the measurement in uncontrolled environments sustainably complicates an accurate and traceable metrology. The regulation pressures in many industries request a metrology that is able to keep pace with these demands.

1.1 Traceable Measurements using Machine Tools

There are different approaches for a traceable LVM in the different fields of large volume manufacturing. Integration of the measurement process into large machine tools seems to be able to improve the process quality and lead to reduced machining waste material, a better conformance with the tolerances required by in directives or even standards. Especially the possibility of one clamping set up allows re-work processes in the same coordinate system and consequently the improvement of the product quality.

2 Task

The objective to integrate the measurement process into the machine tool initially seems to be an engineering problem and many machine tools are yet equipped with a touch probe system that can be automatically loaded. But in fact, the configuration of the measurement system addresses some more technical aspects and scientifical questions that will be focused on in the following chapters. To ensure the comparability of the measurement values the traceability is necessary. The closing of the calibration chain is the main scientific objective within this approach. The approach is concerned with the adaption of known methods for the traceability of Coordinate Measuring Machines (CMM) to the challenges of a machine tool. The traceability can be achieved by the determination of the uncertainty for the measurement process.[1][2][3]

The main challenges are the differences in the kinematic setup of a machine tool and a CMM. The geometric errors of the machine tool influence the manufacturing result and prevent a traceable measurement on the machine tool. Beneath these systematic errors, the environment of the shop floor means the biggest challenge to a traceable measurement as the manufacturing of large-scale devices cannot take place in expensive controlled environments. The dominant uncertainty source for the measurement of large scale devices are in time and space varying thermal effects of the environment and the gravitational distortion of both measuring instrument and measured part. The understanding of the behavior of a multiple-part assembly in an uncontrolled environment is still not detailed enough to predict the displacements within the machine tool structure caused by thermal instabilities and gradients. These challenges are addressed in many research projects and programs in the European research community. Issues such as gravitational sag, thermal expansion, thermal diffusity and thermal effects on instruments and parts have to be tackled by using multidisciplinary approaches involving dimensional and thermal metrology and state-of-the-art modeling.[4] Within in this research field with the named challenges the approach is located.

3 Activities

The research for the development of a concept for a traceable machine integrated measurement process is based on a demonstrator that was set up at the laboratories of the WZL in Aachen. A machine tool of the type HERMLE C 800 U represents a common five axis kinematic for flexible and precise manufacturing of complex parts. The five-axis machine tool has become increasingly common by the fact, that even complex sculptured surfaces can be machined in a single set-up with versatile tools.[5] The machine tool is equipped with different tactile touch probes that can be automatically loaded. There are temperature sensors around the demonstrator and at different locations on the machine structure to measure temperature changes. The measured results can be validated by a standard. There are different standards that can be used such as the Multi-Feature-Check developed by µmetron and ZEISS. For the research activities a specified standard was designed, manufactured and calibrated, that allows checking different tolerances such as position, diameter, coaxiality, straightness, angles etc. Because the standard is calibrated at 20°C, the temperature difference between the calibration device and shop floor will mean a gap in the calibration chain. The CMM of the type ZEISS Centermax closes this gap. It is located in the same environment as the machine tool and works under the same environmental conditions. So the standard can be calibrated on the CMM on the shopfloor and can than be measured on the demonstrator to validate the results.

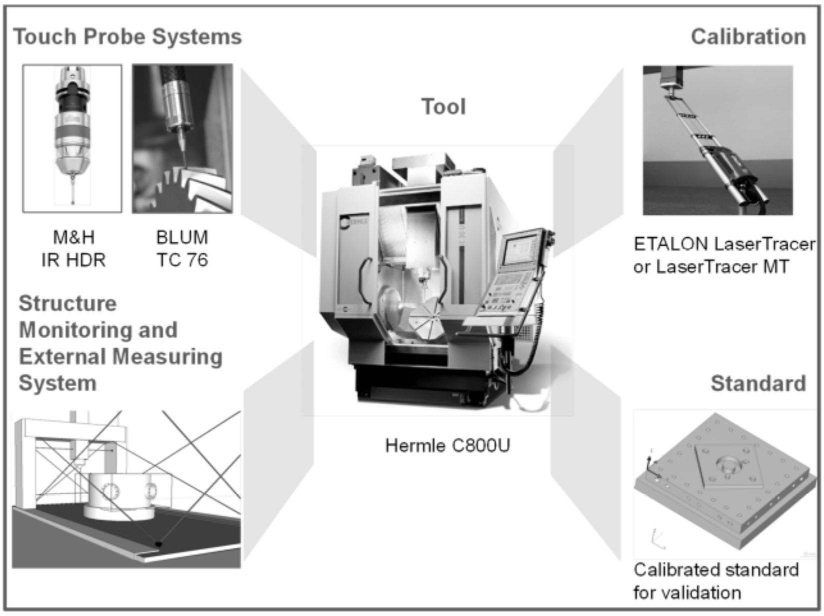

Figure 1: Demonstrator set-up at the laboratory at the WZL in Aachen

Different methods are investigated to be adapted for a determination of the measurement uncertainty for the measurement system. The methods to establish the uncertainty of measurement for a CMM are described in ISO 15530 and in VDI 2617. The general guidance on calculating uncertainty in measurement is given in the ISO Guide 98-3:2008 to the Expression of Uncertainty in Measurement (GUM).[6][7][8]

The described standard will be used for validation by determining the uncertainty as described in DIN ISO 15530 part 3 by using the method of substitution. The experimental approach aims to simplify the uncertainty evaluation by using a calibrated work piece or a referenced standard of a similar geometry and dimension (similarity standards described in clause 5.2). The measurement strategy has to be the same as for the practical measurements. In case of the demonstrator the strategy is set up and the measurement is carried out 50 times. The uncertainty will be determined comparing the means of the measured values to the reference values measured on the shop floor CMM.

The second method is the establishment of the measurement uncertainty by the use of uncertainty evaluation software (UES). The software uses Monte Carlo methods as mathematical algorithms to compute the results. In joint projects with the Physikalisch Technischen Budesanstalt in Braunschweig (PTB) the virtual Coordinate Measuring Machine (vCMM), a UES developed by the PTB and the National Physical Laboratory (NPL) in London, shall be further developed for the uncertainty establishment for machine tools.

A third method is described in VDI 2617-11. The concept aims to determine the measurement uncertainty out of the uncertainty budget. The budget consists of listing each uncertainty source, its magnitude, effect on the measurement result and the correlation with the other sources. [6][7]

For a specific measuring task the uncertainty budget consists of the individual contributions to the uncertainty of measurement. The basis is the mathematical model that takes into account that the measuring result is a function of all influencing quantities. The individual contributions can be taken from available information such as manufacturer's specifications or calibration certificates. The standard uncertainty (u_c) of the result is the squared sum of all contributions (u):

$$u_c = \sqrt{u_1^2 + u_2^2 + u_3^2 + \cdots u_n^2} \quad (1)$$

As the geometric error of the machine tool components and structures is one of the biggest influences for inaccuracy this will also be the main contribution to the measurement uncertainty using the machine tool as a measuring machine.[8] The knowledge of these errors is the basis for further estimation of the contribution to the uncertainty.

The accuracy of the machine tool can be determined by different direct or indirect measurement methods.[9] Within this project, the calibration was done with the ETALON LaerTRACER-System. The LaserTRACER is a self-tracking laser interferometer, which was developed in cooperation with the German Physikalisch-Technische Bundesanstalt (PTB) and the National Physical Laboratory (NPL) in the UK. The laser beam tracks automatically a reflector and determines the distances with highest accuracy in all directions. The reflector is positioned in the TCP of the machine tool. The LaserTRACER tracks the machine tool path out of different positions. The length information can be used for the calculation of the exact position of the reflector and the TCP. Within the project, the machine tool is equipped with the VCS System of Siemens. That allows a compensation of the measured errors in the CNC control. The machine tool is calibrated a second time and the measured values are used for the further steps. The calibration data are necessary information for each of the described approaches.

4 First Results and Outlook

In cooperation with the PTB in Braunschweig and some industrial partners in the working group *Mt-Trace*, the measurement on the machine tool was simulated with the vCMM software. Therefore, the software was adapted to the special challenges of the machine tool. Some more research has to be done to validate the adaptions of the software. The inputs for the model are the following information:

- the machine accuracy,
- the work piece,
- the touch probe,
- the temperatures in and around the machine tool structure,
- the measurement strategy.

The results of the simulation are the uncertainties given for some example features in *Table 1* (Circle Diameter 40mm, touch probe M&H).
The results shall be compared to the uncertainty determined with substitution described in DIN ISO 15530-3. The chosen features of the work piece were measured 50 times. The data were analyzed in Matlab© as needed in the standard. [8] The uncertainty is calculated as described in (1).

$$U = k * \sqrt{u_{cal}^2 + u_p^2 + u_w^2} + |b|$$

u_{cal}: *standard uncertainty calculated from the uncertainty of calibration of the calibrated workpiece (stated in the calibration certificate)*

u_p: *standard uncertainty of the measurement process that is determined with* $u_p = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(y_i - \bar{y})}$ *and* $\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$

u_w: *standard uncertainty influenced by the material of the work piece* *b:* *systematic deviation between the values y_i indicated by the CMM and the calibration value x_{cal} of the calibrated workpiece* $(b = \bar{y} - x_{cal})$

n: *number of measurements*

k: *coverage factor*

The results calculated with the data of the repeated measurements can be compared to the simulated values for the measurement uncertainty.
The differences between the uncertainties determined by different methods seem to be influenced by the touch probe uncertainty. The touch probe uncertainty could not yet be determined as described in DIN ISO 230-10, caused by the machine tool control. Some more evaluation in this field as well as in testing different touch probes has to be done.

Table1: Measurement Uncertainties

Feature	Adapted Method	Measured Value	Uncertainty
Circle Form	DIN 15530-4	0,0124	0,0047
	DIN 15530-3	0,0132	0,0039
	Certificate	0,0034	0,0012
Circle Diameter	DIN 15530-4	40,0048	0.0042
	DIN 15530-3	40,0496	0,0046
	Certificate	40,0472	0,0011
Straightness A	DIN 15530-4	0,0024	0,0032
	DIN 15530-3	0,0028	0,0023
	Certificate	0,0039	0,0011

4.1 Traceable Measurements on machine tools

The next steps within the project will address in some more detail the comparison of the different approaches. The determination of the uncertainty by the uncertainty budget (VDI 2517-11) is in progress. The results will also be compared to the results of the other approaches. Hereinafter the concept for traceable measurements shall be adapted to the challenges of large machine tools (axes > 5m) and Multi-Technology- Production Systems (MTP). MTP are machine tools with different integrated manufacturing processes. The demonstrator at the WZL is part of the Cluster of Excellence *'Integrative Production Technology for high Wage Countries'* at the RWTH Aachen and has been funded by the German Research Foundation DFG. It consists of two workings spaces, a common spindle and a robot that handles an innovative laser welding process. Integration of different production processes means the loss of semi-finished products that can be used for a quality control process. Consequently, the quality inspection process has to be integrated into the machine tool as well.

Figure 2: MTP at the WZL (Chiron-Werke GmbH, DFG, WZL RWTH Aachen)

4.2 Thermal Effects

The topic of thermal influences on the machine tool structure has to be intensively investigated, as it is critical for the measurement process as well as for the manufacturing process.[10] The main objective is to predict the static and dynamic behavior of the machine structure under thermal load. The modeling of thermal effects within the machine structure is very complex. Multiple national and international projects have been established this research field. Within a European Project under the lead of the NPL different National Metrology Institutes and universities trying to improve the necessary modeling to understand and predict the behavior of large multi-component structures in non-ideal measurement environments. This will for example be supplemented by in situ dimensional and thermal measurement data at critical points. The first step for a complex modeling of a multi-component structure such as a machine tool or a complex work piece is the precise understanding of the effects on the structure. To improve the knowledge a new absolute measuring system based on a frequency scanning interferometer (FSI) shall be further developed and enabled for a permanent surveillance of the machine tool structure. The system was developed by the University of Oxford, the NPL and ETALON AG. Once the system is integrated into the machine tool structure, the static and thermal behavior of the machine tool can be mapped. To focus on thermal influences the machine tool will be placed in a new thermal chamber at the WZL. This chamber allows a controlled change of the thermal surroundings of the machine. In short term, this shall be used for the stability of the thermal surroundings during the measurements. In long term, the collected data shall allow to improve the known rigid body models of machine tools by extending it with dynamic structures.

References

[1] Trapet, E.; Franke, M.; Härtig, F.; Schwenke, H.; Wäldele, F.; Cox, M.; Forbes, A.; Delbressine, F.; Schellekens, P.; Trenk, M.; Meyer, H.; Moritz G.; Guth, Th.; Wanner, N.: *Traceability off Coordinate Measurements According to the Method of the Virtual Measuring Machine*, Final Project Report, 1999.

[2] van Dorp, B.; Delbressine, F.; Haitjema, H.; Schellekens, P.: *Traceability of CMM Measurements,* ASPE 1999 Annual Meeting, Monterey (1999)

[3] Flack, D., *Virtual CMM*, QMT- Quality Manufacturing Today, Dec 2012

[4] Lewis, A., *Large Volume Metrology in Industry*, Joint Research Project in EMRP Programme.

[5] Lin, Y.; Shen, Y.; *Modelling of Five-Axis Machine Tool Metrology Models Using the Matrix Summation Approach*, Washington D.C., 2003

[6] Hernla, M.: *Uncertainty of coordinate measurements*, QZ, 2010

[7] VDI 2617: *Accuracy of coordinate measuring machines-Characteristics and their testing*, Beuth Berlin

[8] DIN ISO 15530 *Geometrical product specifications (GPS) Coordinate Measuring Machines (CMM)*, Beuth

[9] Zhu, S., Ding, G. Qin, S., Lei, J.,, Zhuang, L., Yan, K.: *Integrated geometric error modelling, identification and compensation of CNC machine tools*, International Journal of Machine Tools & Manufacture, 2012

[10] Mayr, J. et alt., *Thermal Issues in Machine Tools*, CIRP Annals, Manufacturing Technology, 2012