XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6−11, 2009, Lisbon, Portugal

KNOWLEDGE-BASED OPTIMISATION OF THE TACTILE SCANNING PROCESS ON CMM

Prof. Dr.-Ing. Robert Schmitt , *Dipl.-Ing. Susanne Nisch*

Laboratory for Machine Tools and Production Engineering WZL of RWTH Aachen University, Germany,
R.Schmitt@wzl.rwth-aachen.de
S.Nisch@wzl.rwth-aachen.de

Abstract − Today the scanning-technology on coordinate measuring machines (CMMs) is used for tactile detection of form deviations. Many companies apply CMMs instead of form measuring devices because of their high flexibility and the possibility of fast workpiece inspection. However, the kinematic of CMMs is more complex than the one of specialized form measurement devices. Dynamic effects, like centrifugal force of roundness measuring, result in a rising measurement uncertainty. The right setup of scanning parameters, like point density and scanning speed, is a challenging task. It is up to the machine operator because guidelines for the setup of optimal parameters do not exist. The dynamic characteristics of the used CMMs are not sufficiently identified and the detection of the measuring task dependent uncertainty is very complex. At the chair for Production Metrology and Quality Management of RWTH Aachen University the characteristic behaviour of tactile scanning CMMs are analysed. These studies built the basis for the practical and object oriented optimisation of the measurement strategy. An actual research project deals with the development of optimisation strategies by considering the maximum allowed measurement uncertainty. A knowledge-database was defined containing basic information about the used CMM, ranges for parameters and the main dynamic characteristics based on experiments.

Keywords: tactile form measurement**,** scanning on CMM, efficient measurement

1. INTRODUCTION

Industrial Metrology provides the necessary information for improving product quality and production processes. Measuring results do not only provide the basis for customer-supplier relationships, but also for decisions in process chains. Comparable results are needed that require information about the conditions and applied technology for measurement [1], [2].

The application of industrial production metrology is always connected to the right consideration between the most efficient way of use and the targeted measurement uncertainty. The choice of the best measuring strategy is complicated for processes with non-linear correlations between influence quantities and uncertainty, because of rising measurement durations and costs. This problem is typical when using scanning technology on tactile coordinate measuring machines [3], [4]. There are multitudes of variable parameters, like scanning speed, point density and force, that influence the dynamic characteristics of coordinate measuring machines and the friction between the workpiece surface and the probe [3], [5]. During data processing, outlier elimination and filtering the resulting measuring deviation changes in a nonlinear way and the coherences between parameters, specific machine characteristics and measuring results cannot be quantified [6]. Accurate specifications for parameters, that allow a qualified and human-independent choice of adjustment, do not exist because of their dependence from workpiece surface and specific characteristics of every measurement device [7], [8].

The right adjustment of parameters is complicated and results of different CMMs are not comparable because of different conditions during the measuring process. In addition, the evaluation of measurement uncertainty for form measurements on CMMs does not exist. The characteristic limit values for form deviation MPE_{RONt} and scanning MPE_{THP} according to EN ISO 10360-4 [9] only consider values for the acceptance and reverification tests of CMMs [3]. However, the description of quantified coherences between the scanning parameter and the resulting form deviation is not possible. But they are required for the object oriented definition of the measurement strategy. Therefore, the development of a method to choose the value of parameters, by considering all significant conditions and maximum allowed measurement uncertainty, is necessary. The object oriented optimisation has to be requiring the influences of the workpiece as well as of the CMM characteristics.

The basis for an object oriented and uncertainty dependent adjustment of scanning parameters is knowledge about the coherences between influencing parameters and results. Therefore, the influences and interactions of the scanning process were analyzed through experimental methods and stored in a knowledge database. This information enables the evaluation of the main transfer characteristics of the scanning process.

With the technical flow chart of the measuring system and the transfer characteristics the process of scanning was simplified in a model. That supports the analysis of the scanning process and provides the basis for the evaluation of

ISBN 978-963-88410-0-1 © 2009 IMEKO

the measurement uncertainty by simulation. Because of the strong coherences between the workpiece surface and the measurement uncertainty several analyses are necessary.

The transfer characteristics depend on the producer and the type of the CMM. However, the dynamic characteristics of comparable CMMs are very different. Hence, the specific detection of the transfer characteristics for every CMM, for the tactile scanning, is required. Using specifically developed multiwave standards the characteristics are detectable for the considered dimensions.

In this paper the methods for achieving the CMM specific transfer characteristics is presented by demonstrating selected key results of the analyses of CMM specific behaviour. Besides, object and task oriented strategies for optimisation of measurement strategy for form measurement on a CMM are proposed.

2. METHODICAL ANALYSIS

2.1 A model for form measurement

In order to reach a systematic evaluation of best fitting parameters, the implementation of influences and correlations in a practical model is required. This model has to include the process of detection as well as the data processing and filtering, because of the significant transformation of data.

The model, that is illustrated in Fig. 1., consists of transfer elements with a specific function based on experimental data, which considers the influences caused by uncertainty of measuring systems. The “scanning” part provides the simulation of surface profiles that are close to reality. The systematic and the random influences of the measuring setup are analysed and implemented. Therefore, two hypotheses are established for the simulation of the real scanning processes: systematic deviations generated by the scanning process could be described by a transfer function and random deviations cause a Gaussian white noise.

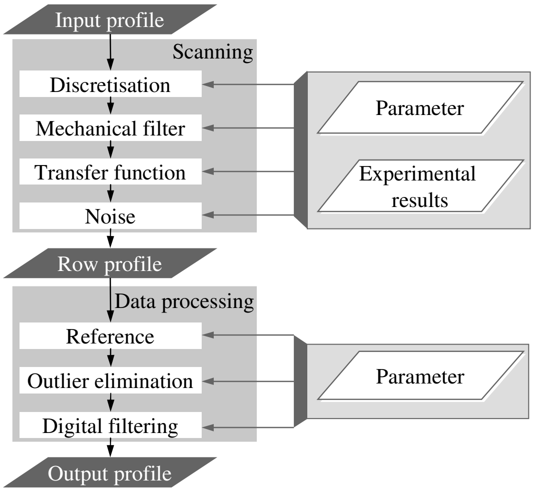


Fig. 1. Layout of the model for analysis and simulation of form measurement on CMM.

In form measurement, the row profile is processed to minimize the influences of outliers and roughness on the results. To analyze the influences of outlier elimination and filtering on the measurement uncertainty the row profile is proceed like real measured profiles. Afterwards, the reference is calculated for the evaluation of the form deviation.

2.2. Wave standards

For a correct analysis of these influences and interactions, special wave standards have been developed with several functional and referencing features. Besides structured features for roundness at the outer and inner diameter, areas for flatness and straightness are included. The developed standards represent a large spectrum of workpieces because of their high total form deviation, resulting from different superimposed sinusoidal waves with defined frequencies and amplitudes. In Fig. 2 the small multiwave standard is illustrated. Structured areas for roundness and flatness have superimposed waves with a frequency of 5, 15, 50, 150 and 500 UPR and amplitudes of 4 µm. E.g. the form deviation of the area of outer roundness that is shown in (2) in Fig. 2 is 14 µm. An advanced multiwave standard was developed with an additional area for straightness. Its superimposed waves have wavelengths of 0.8, 2.5 and 8 mm.

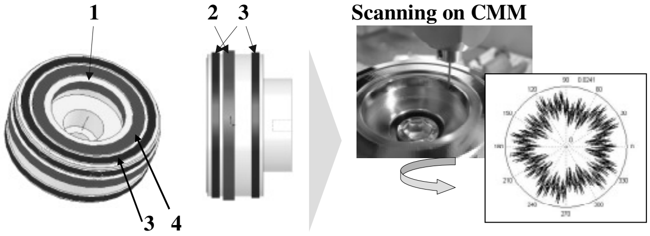


Fig. 2. Illustration of a multiwave standard having a diameter of 80 mm with structured areas for inner roundness (1), outer roundness (2) and flatness (4) and non-structured areas for justification (3)

The multiwave standards are aptly suited for the analysis of specific coordinate machine characteristics because the machine specific deviations of profiles are reflected in the noise of measured and Fourier transformed signals.

However, the results must not be transferred to workpieces with other surface structures. Several studies showed that the measurement error of the dynamic behaviour depends on the real form deviation of the workpiece surface. With its high form deviation the multiwave standards cause measurement errors, resulting in a large measurement uncertainty.

2.3. Methodical analysis of parameters

According to ISO 1101 the form deviation is evaluated by two concentric circles, two parallel lines or two parallel planes with a minimal radial or orthogonal distance. The transfer accuracy of the real profile does not determine the calculation of elements. Hence, this method is not capable for analysis of coherences between parameters and results.

This is demonstrated by an example in Fig. 3, that shows the coherences between scanning speed and roundness on a multiwave standard.

Because of dynamic machine velocity, the form deviation increases with faster scanning according to the calibrated form deviation of the multiwave standard. When the scanning speed reaches the critical value the probe is partially lifted from the workpiece surface because of the centrifugal force surpassing the measuring force interacting in the reverse direction. This results in a smaller form deviation although the measuring error is bigger.

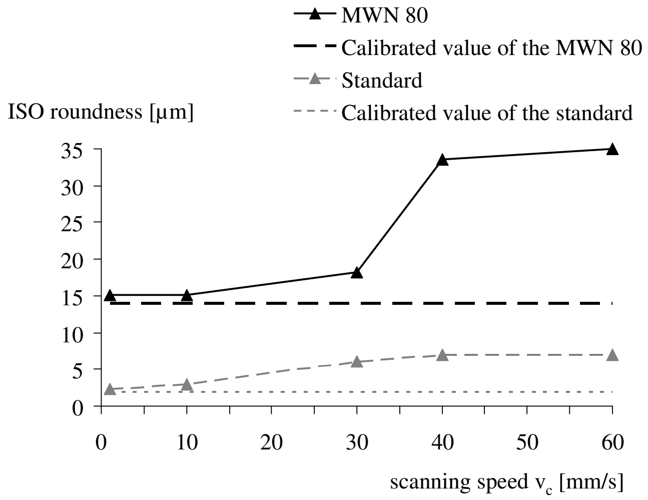
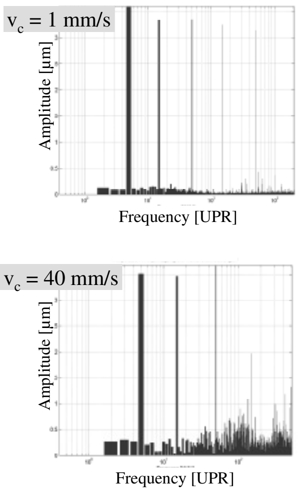


Fig. 3. Form deviation (roundness) measurement according to the ISO 1101 at the multiwave standard (MWN) with structured surface (∅ 80 mm). In addition, a normal standard with minimized form deviation (∅ 100 mm) with different scanning speeds.

In Fig. 3 the results of a measured standard with the diameter of 100 mm and a very small form deviation of 2 µm is imaged. To increase the scanning speed results in a bigger form deviation, too. But the gradient is much smaller, compared to the multiwave standard. That means that the structure of the surface influences significantly the scanning process. The transfer behaviour depends on the structure of the workpiece surface and its diameter. Having a small proportion between form deviation and diameter the radius of curvature in every single point is very small and the probing direction changes often. To measure points on the surface a continuous changing of probing direction is required. The risk of a probe vibration at probing rises with higher form deviation. At workpieces with a small form deviation and periodic waves with big wavelength the curvature on workpiece surface changes less often. Hence, the continuous measurement is possible and the dynamic error caused by vibration is reduced.

For detection of the real influences of parameters the Fourier transformation is suited [10] and used for analysis in Fig. 4. With rising scanning speed, the amplitudes of the 5 dominating waves of the multiwave standard are reduced and the amplitudes of other frequencies rise. This effect intensifies with rising frequency and depends on the point density of the measured profile.



Amplitude 5 UPR =	3,60 µm
Amplitude 15 UPR=	3,33 µm
Amplitude 50 UPR =	3,38 µm
Amplitude 150 UPR =	3,25 µm
Amplitude 500 UPR =	3,14 µm
$A_{q,noise}$=	0,37 µm

Amplitude 5 UPR =	3,50 µm
Amplitude 15 UPR=	3,47 µm
Amplitude 50 UPR =	3,68 µm
Amplitude 150 UPR =	1,98 µm
Amplitude 500 UPR =	1,33 µm
$A_{q,noise}$=	2,31 µm

Fig. 4. Analysis of form measurement results of two measurements with a scanning speed of 1 mm/s and 40 mm/s of the multiwave standard (∅ 80 mm) by Fourier transformation.

Using multiwave standards, the real profile could be detected by calibrating it on a form measuring device with high accuracy. If the Fourier transformation is used for analysis of calibration data of multiwave standards, the profile of dominating waves DFT $\{F_{Dom}\}$ is detectable. Analyzing a profile measured on a CMM the Fourier transformed profile looks different to the calibrated profile because of a super positioned error profile called noise A_{noise}. For the analysis of the measurement process forcing errors on the measured profile, A_{total} has to be separated using equation (1).

$$A_{noise} = A_{total} - DFT^{-1}\{F_{Dom}\} \tag{1}$$

$$A_{q,noise} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} A_{noise}{}^{2}} \tag{2}$$

The noise signal enables the evaluation of the reliability of transferring particular parts of the profile, depending on values of the input parameter.

Through the application of Design of Experiments (DoE) methods, the basic characteristics of scanning on coordinate measuring machines are systematically analyzed and quantified. With preliminary experiments the significant parameters were identified. Necessary information about limits of the parameters are used for definition of experimental limits and the steps of parameters. For example the maximum possible scanning speed of a CMM that can measure 450 points per second is 45 mm/s with a point distance approximately 0.1 mm. Therefore the maximum possible scanning speed is limited, dependent on the required point density.

Because of the high number of important parameters, full factorial experimental designs are not useful. They would require a larger time period for the experiments and analysis without benefit, comparing to reduced experimental designs. Not all results are significant and important for analysis of errors of scanning process. There are several interactions between the parameters, but the main interactions of interest concern the scanning speed.

In Table 1 the significant interacting parameters concerning the scanning speed are listed. Some of the parameters, e.g. the point density, influence the results for form measurement at slow scanning. If the scanning speed is increased, the influence of such parameters increases, too. Other factors like the orientation and position of the workpiece in the measurement volume have no significant influence on the measurement result at slow scanning. However, the scanning speed is increased, the orientation and position of the worpiece is very important for the results of measurement. This is caused by the asymmetric setup of the universal CMMs that are studied. These CMMs are only one-sided driven. Influences, which are caused by dynamic effects of the cinematic chain, change in the measurement volume.

The primary objective while preparing the experimental design, is to reduce experiments by mixing experiments of interacting parameters, with experiments of non-interacting parameters. On the basis of preliminary experiments, significant interactions are detected, that are comparable on different machines. The vibration of probes on surfaces with small radius of curvature or the dependence from the workpiece orientation must be required. They only vary in value and direction. Based on the research, reduced experimental designs are available that only have to be adapted to a relevant target.

The main results of the previous analysis are the main influencing parameters of scanning that are useful for the optimization. The scanning speed is the main influencing factor according to measuring time. The other parameters like point density or measuring force have to be determined considering the scanning speed. In addition, several factors are important that are limited adjustable like the orientation of the workpiece and the probe configuration. Therefore advices can be given.

Table 1. Example from interacting parameters of scanning processes, with the parameter scanning speed – influence on results of form deviation.

Parameter	slow scanning	fast scanning
Point density	◕	●
dimension	◑	●
Measuring force	◑	◕
Probe stiffness	◑	◕
Surface characteristics	◔	●
Orientation	○	●
Position	○	●
○ Negligible coherence between parameter and result		
● Strong coherence between parameter and result		

3. DEFINITION OF CMM SPECIFIC CHARACTERISTICS

For object oriented optimization of scanning parameters according to the maximum allowed measurement uncertainty, the machine specific transfer behaviour is defined in the CMM specific characteristics. Using the already described methods a knowledge base is built. Therefore the following tree types of parameters are defined depending on the CMM:

- Non-adjustable parameter, containing the scope of the CMM, limits of variable parameters, special characteristics like values for MPE, the resolution of scales, maximum detectable points per second and specific kinematic characteristics not influenced by the variable parameters. These characteristics of the CMM are partially evaluated by the producer of the CMM and quoted in the certificate of the CMM.
- Limited adjustable parameters are variable parameters like the probe configuration or measuring direction on the CMM. Because of the measuring task and the machine behaviour their values are limited. Mostly there is only one possible adjustment.
- Variable parameters, like scanning speed, point density and measuring force can be adjusted independently from the non-adjustable and the limited adjustable parameters. Because of the specific dynamic characteristics of the CMM there are strong coherences. Hence, the variable parameters are evaluated after adjustment of the other parameters.

Before identifying the best suitable values for parameters the scanning performance base is defined, including non adjustable and limited adjustable parameters already adjusted to the given measuring task. For example the characteristics of CMMs vary depending on the coordinates used for measuring and the orientation of the workpiece. Measuring in different directions the probe configuration varies. In addition there are different forces in the z-axis or x-axis for the main direction because of the non symmetric construction of CMMs. The scanning performance base builds the process window for variation and optimization of variable parameters.

4. OPTIMIZATION OF SCANNING PROCESS

To optimise the scanning process, the CMM specific behaviour and the measuring task are important. The definition of universal strategies that are transferable between different CMMs is not possible. The primary objective for the optimisation are reducing time for measurement and enabling the comparability of measurement results.

The length of measuring time only depends on the actual scanning speed. The defined scanning speed is limited by the required number of points because of the maximum sampling rate. To measure high structured surfaces requires a higher point density than the measurement of a surface with small deviations. In official standards suggestions for the sensible definition of the point density are made. Because of the dynamic characteristics of CMMs the useful scanning speed is less than the limit of the scanning speed. This is caused by the influence of surface structure. In relation to the scanning speed and point density the measuring force has to be considered. The measuring force minimizes the adverse effects like probe vibration or micro-jumps. To transcend the critical value of the measurement force, damages on the probe configuration or workpiece surface are caused. Therefore, the producers of CMMs give suggestions according to the measuring force. However, before defining the values for variable parameters the conditions of the measuring process have to be specified. To optimise the scanning process a four-stage approach is proposed.

The first stage deals with the preparation of the measuring system, the workpiece and the probe configuration. Because of the measuring task the possibilities for position and orientation are limited. Only suggestions for the optimised preparation are possible. Based on the analyses with the multiwave standards a qualitative detection of position dependant influences on measurement is possible. With the second stage variable parameters are defined which can be optimised against a limit that is independent on the measuring process. This concerns the measuring force and the point density. With the third stage the value for the scanning speed is defined. On the basis of the knowledge database the coherence between scanning speed and measuring error is detected qualitatively for the adjusted parameter. To validate the used values for the scanning parameters, comparative measurements are necessary in the fourth stage. Therefore the workpiece is measured two times, first with the defined scanning speed and second with the minimum possible scanning speed. The determined measurement error of the fast scanning is only caused by dynamic effects. Other influences of measurement process are not considered. The calculated error for form measurement must not exceed a threshold that is defined by the tolerance.

In industrial applications, many measuring tasks are similar. Saving the optimised values according to the measuring tasks in the knowledge-database is sensible. If the used CMM is checked regularly by the multiwave standards according to the dynamic behaviour under defined conditions, these optimised values for scanning parameter are useful for future measuring tasks.

5. CONCLUSIONS

In this paper methods are established, used for the experimental development of a CMM-specific knowledge database, enabling the adjustment of parameters for scanning. The main objective is the choice of values of scanning parameters to maintain the allowed scanning speed.

In spite of reduced experimental designs, the necessary effort of the method is high because of the required detection of machine specific behaviour with special standards. Therefore new strategies have to be developed reducing the experimental work of the user without decreasing the density of information.

Previous experiments showed a strong correlation between the detected coherences at scanning as well as the dimension and surface characteristics of the workpiece. The achieved results and coherences are not transferable to bigger workpieces or other structured surfaces. At present there are many restrictions to the use of the method. Additional analysis will serve to expand the method to any workpiece dimension and surface. Therefore experiments with real workpieces from different manufacturing methods will be performed.

The use of the scanning performance base supports the comparability of measuring results because on one hand there is more information about the measuring process and on the other parameters are adjusted based on real CMM characteristics and not only on the knowledge of operator.

However, the accurate optimisation of the measurement strategy is not possible without the measurement uncertainty, because of their importance to the acceptance of the product and the comparability of measurement processes. The primary objective of future analysis is the development of methods for the fast estimation of the measurement uncertainty. The presented model builds the basis for the simulation of the measurement error and supports the evaluation of systematic influences. In the future these methods will support the objective and comparable use of CMMs for the form measurement.

ACKNOWLEDGMENTS

The authors would like to thank the “Deutsche Forschungsgemeinschaft” for funding the research of this project.

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