# ESTIMATING THE UNCERTAINTY OF THE MEASUREMENTS PERFORMED USING THE COORDINATE MEASURING SYSTEMS

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**Abstract –** Today many different systems are working in accordance with the idea of coordinate measuring technique. There is possibility of using the same measuring software with optical or contact coordinate systems as well as with a 3d scanners (structural or laser light). This gives the opportunity to use different measuring systems for the same tasks. Consequently, it is possible to build faster and more efficient techniques for controlling the production. For example: a fast check of car body production with 3d scanner systems and one per shift accurate measurement of the same element with reference Coordinate Measuring Machines. The main purpose of measurements in industry is assessment of the conformity or nonconformity of the production with the specification. The specification can be written in classical paper documentation or saved in CAD-file. Never-mind how specification is written or saved, the uncertainty of the measurement should be taken into consideration, according to the ISO 14253-1 guideline. In the case of a supplier - to his benefit, by extending the area of conformity and in the case of production control - by reducing the area of conformity.

**Keywords** LCMM, calibration, uncertainty

## 1. INTRODUCTION

Despite the concept of uncertainty is being used for almost 30 years it is still hardly definable. On one hand, according to the VIM dictionary measurement uncertainty is defined as a non-negative parameter characterizing the dispersion of the quantity values being attributed to the measured quantity. So it is defined here similarly to the statistical approach.

On the other hand, uncertainty is defined as the area in which the actual value of measured quantity lays with determined probability.

The more sophisticated measurement model becomes, both definitions becomes more inconsistent. And it is important especially in the case of calibration uncertainty where it is important to estimate the distributions of each uncertainty components as well as to determine the area around the measurement result, in which the true value lays.

The latter approach is important because of the utilitarian use of measurement uncertainty.

The research on the methods for estimating coordinate measurements ongoing for nearly 40 years. It should highlight here the German PTB center, who was the first the developer of a virtual machine [7]. Cracow University of Technology developed two different approaches to the subject, analytical virtual machine [6], and using the matrix method [4]. Similar work has been taken in Bielsko-Biala led by Jakubiec [3]

## 2. COORDINATE MEASUREMENT

Coordinate measurement can be defined as a measurement in which the primary measurement is given as the measurement of the points coordinates. These points then form the basis for determining the relevant geometric elements, which are then assessed.

Coordinate Measuring Systems are a very large group that includes both contact systems (Coordinate Measuring Machines, Coordinate Measuring Arms, Laser Tracking Systems etc ...) and contactless systems (Laser Radar systems, structured light scanners, computed tomography), metrologists are more often facing the multisensor systems where the structure of the machine is only used to transport various types of probe heads used for collecting points in both contact and contactless manner. What unites these measuring systems, based on different measurement methods and having different kinematic structures, is the principle of measurement. That brings user to the situation in which he can work with all of these systems using the same software.

With the increasingly widespread use of coordinate measuring techniques in the industry, the role of the appropriate evaluation of uncertainty of measurement is becoming more important. The most common mistake met in metrological practice is taking the value of the maximum permissible error as the uncertainty of measurement carried out by used coordinate system. It is an approach that is transferred from the simple measuring devices on which the measurement is predominantly direct and one-dimensional. As an example the caliper can be given.

Large variations in measuring tasks that can be performed using coordinate measuring systems results in the fact that this approach cannot be applied. Especially in cases where the nature of the measuring task differs significantly from the methods of measurement used during assessing the accuracy of the system.

## 3. SOURCES OF UNCERTAINTIES IN COORDINATE MEASUREMENTS

According to ISO 14253-2:2011 it is possible to point out 10 potential sources of measurement uncertainty :

- Measurement equipment
- Reference element of measurement equipment
- Software and calculations
- Metrologist
- Enviroment of the measurement

- Measurement object
- Measurement setup
- Definition of the workpiece
- Measuring procedure
- Physical constants

Considerations about the sources of uncertainty should start from the measuring equipment. The tool, which is used to perform the measurements is the huge source of errors and the values that affect the accuracy of measurement. First of all, a matter of measuring tool repeatability. It is a measure of the potential accuracy that can be achieved after minimization of other influences. One should also pay attention to the changes in tool geometry due to the thermal influences. They can be caused not only by the long-term factors as the winter-summer temperature differences, but for example also a result of switching off the lights for a night. Subsequent device temperature stabilization might take even eight hours.

Another important element is the length standard that was used in coordinate system. In addition to the measurement repeatability, it is another element that indicates the potential accuracy of measurement while minimizing other influences. Current technical development allows for the usage of incremental scales with a resolution of a few nm. When laser interferometers are in use, it is possible to achieve values of less than 1 nm. It should be however pointed out, that currently achievable and verified accuracies are about 100 times larger.

Applied software is a very important factor, especially in the case of the newer coordinate devices, in which the measurement is based on the point cloud acquisition. Application of the different methods of filtration may be critical to the results of measurements. The complexity of this type of measurement is so large that in many cases, software companies "hide" the key parameters of filtering, providing just some simplified features.

The operator of the measuring equipment, especially his experience in performing the measurements cannot be overestimated, especially in the case of manual machines. In the case of automated machine, his role, and so the influence are reduced.

Measurement environment is one of the most important factors dealt with, especially considering the high accuracy CMMs. It is indispensable in this case to consider the effect of temperature or humidity. Both for their absolute value and its changes during the measurement. The variability of the workpiece geometry in the case of temperature changes is difficult to assess. In this case, it is possible only to reduce its impact, e.g. through an appropriate air-conditioning system allowing to reduce the variability of environmental conditions. An example of such a system is the air-conditioning in the Laboratory of Coordinate Metrology, which allows to reach the temperature variation of 0,05 $^{o}$C/h.

It is difficult to talk about the influence of the measurement object on the coordinate measurement uncertainty. This source is often overlooked due to the fact that it is being the object whose geometric properties are assessed. However, secondary characteristics of this object may influence the evaluation of the measured characteristics. Both roughness and form error can affect the result. An example is the measurement of the inner cylinder diameter, where the result will depend on the localization of measuring points. For contact measurements, there will be a problem of deformation, particularly for the elements made of plastic or thin-walled material. For non-contact measurement the question of measured surfaces reflectivity is important.
A very important element are also the changes of the measured geometry during the measurement, associated with the thermal expansion.

Incorrect mounting of the measurement element, effecting in deformations or possibility of uncontrolled movements is the impact, which is difficult to estimate. Therefore, the aim is to eliminate this effect.

Proper definition of the measuring task is extremely important, especially if we are dealing with a task such as distance of the two planes. In this instance, if it will be sufficient to bring this task to the determination of plane – point distance? If yes, the next question is, which point should be taken for calculations, the centroid of the measured points or the most distant that is possible to identify during measurement?

The measurement procedure, in this case, both the number of points and their distribution on the measured object can lead to achieving different results. This variable is related to the geometry of the object. On the other hand, the more points is measured on the surface the smaller is the variability of the results due to their different spreading.

The last point mentioned by the ISO 14253-2 is the current state of knowledge regarding the physical constants. At present, coordinate measurement accuracy estimated at the level of 0.1 $\mu$m does not require to take these factors into account.

The above-mentioned components are only a proposal elements that should be taken into account when considering the coordinate measurement uncertainty. They are not independent from each other. For example the linking of the geometric properties of the surface with chosen measurement strategy and their influence on the result. It is important, however, to realize the differences between the accuracy of the measuring device and the uncertainty of measurement performed using this device.

## 4. Determination of coordinate measurement uncertainty

### *4.1. ISO 15530 standard*

In case of the determination of coordinate measurement uncertainty, the description of used methods is contained in ISO 15530 standard series. Currently the standard describes two methods: substitution method (of comparative measurement) [1] and the virtual machine method.

### *4.2. Method using calibrated workpieces - substitution method*

The method described here is predisposed to be used mainly in calibration laboratories, for typical geometric elements. It is based on the use of dimensional standards, of which the shape, size and material is the same as those of measured element. This restrictions, allow the method to be used in limited way in the industry, only in the case of mass production where the same shapes are checked multiple times.
In this case, one of these elements can be calibrated and used as the reference element for comparison with the remaining elements.

In this method, the uncertainty can be expressed by formulae:

$$U = k \cdot \sqrt{u_c^2 + u_p^2 + u_w^2} \quad (1)$$

where:
$u_c$ - uncertainty component connected with calibration of standard,
$u_p$ - uncertainty component connected with measurement procedure,
$u_w$ - uncertainty component connected with measured object

Systematic error is determined as a difference between mean value and real value of standard.

$$e_b = \bar{x} - x_p \quad (2)$$

If the conditions regarding similarity are met, the result of measurements should be corrected by an error determined in the equation (2). However, there is also the possibility of extending the uncertainty using resulting error, by replacing the error $e_b$ for the uncertainty contributor $u_b$. It is possible to use especially in a situation where there is not entirely possible to satisfy similarity conditions such as impossibility of using the same measurement strategy.

### *4.3. Multiple measurement strategy*

Multiple measurement method was conceived in order to allow the execution of calibration using the length standards, but without having to meet such strict requirements regarding similarity. Despite the works under this method were started by the Standardization Committee it was not officially released as a standard. It was based on determination of the uncertainty components connected with the measurement repeatability $u_{\text{rep}}$, reproducibility associated with different orientations used $u_{\text{geo}}$, the uncertainty associated with using length standards - $u_L$ and ring standard or spherical standard $u_D$, as well as component related to the thermal influences, $u_{\text{temp}}$.

This method has been adapted for calibrations performed in the Laboratory of Coordinate Metrology. Currently it is the only method that allows full use of Coordinate Measuring Machines capabilities.

What is important, both methods used for measurements of the same object does not give the same results, which is important if they are considered to be used for calibration.

In Fig. 1 the results of calibration of the ball-bar standard using both described methods were presented.

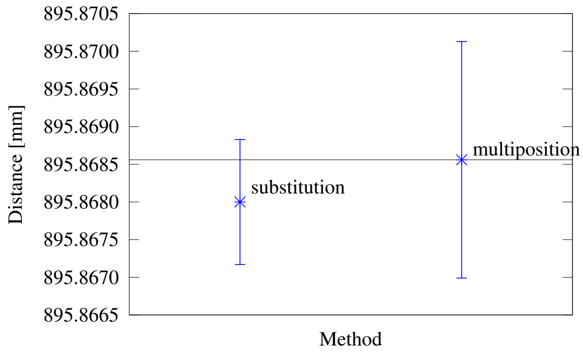


Fig. 1. Comparison of substitution method and multiple measurements method used for calibration of ball-bar standard

Tab. 1. Results of methods comparison

| | | |
|---|---|---|
| Substitution | $X_s$ = 895,8680 mm | $U_s$ = 0,83 [µm] |
| Multiple measurement | $X_m$ = 895,8685 mm | $U_m$ = 1,57 [µm] |

Uncertainty determined using multiple measurement strategy method (1,57 µm) is almost twice larger than this determineg using substitution method (0,83 µm). Parametrer $E_n$ determined according to equation (3) was equal to $E_n = 0.32$ which is enough for stating that both methods are comparable [2].

$$E_n = \frac{X_m - X_s}{\sqrt{U_m^2 + U_s^2}} \quad (3)$$

Both methods discussed here are based on the idea of comparative measurement. Comparative approach can be treated in this case as a classical approach, whereby the possibility of its application is limited. It needs huge base of a material standards which must satisfy similarity conditions (the same material, similar dimensions, geometry that allows for usage of the same strategy), however, this method allows to achieve in laboratory conditions uncertainties at the level of $U_s = 0{,}3\ \mu m + 0{,}6 \cdot L \cdot 10^{-6}$. In the case of multiple measurement method uncertainty was estimated at the level of $U_m = 0{,}6\ \mu m + 0{,}7 \cdot L \cdot 10^{-6}$. Maximum permissible errors for machine on which measurements were done are equal to $MPE(E0) = 0{,}8\ \mu m + 2{,}5 \cdot L \cdot 10^{-6}$.

### *4.4. Virtual Coordiante Measuring Machine*

Development of a system for simulating the errors of the measurement done on Coordinate Measuring Machines is not an easy task. Currently, this issue is regulated by the ISO 15530-4 standard. One of the key elements here is development of a mathematical model of machine errors.

These errors can be divided into two categories, the systematic errors and random errors. For each of them, different techniques of determination must be developed. In the case of systematic errors, description/simulation of changes made by the ambient conditions and description of other errors (for example geometric errors) systematic part are crucial. In the case of random errors, it is important to determine the probability distributions of these errors.

Construction of the model is also related to the design of the machine. In the best known coordinate system - the CMM, it is possible to distinguish two main parts. Machine as a device for carrying and measuring positions of probe and a probe head, which is responsible for identification of contact between stylus and measured object. For each of them, it is required to develop separate models that simulate both systematic and random errors.

If the machine also uses an indexing or rotary probe head it will be necessary to develop the appropriate model for its errors.

In the case of this method, it should be also noted that an important element is the way of connecting the results of this method with other uncertainty components listed in the first chapter. The simulation of machine errors is itself an important part but not the only one during estimation of coordinate measurement uncertainty.

Another problem to solve is linking the virtual machine with metrological software. Currently, the features that are determined during the measurements are not only the geometric features of workpieces or relationships that occur between them. More and more often there is a problem of determining the deviation between measured object and its ideal CAD model. An additional question is what algorithm should be used for determination of the reference geometries out of measured points. Using of self-developed software instead of machine one may lead to situation in which results may differ from those that would be determined using machine software used during measurements.

As the two previously mentioned methods were dedicated for coordinate measuring machines, the virtual measuring machine could also be used on other coordinate systems. The concept is based on an appropriate separation of subsystems responsible for the individual measurements and then development of a suitable method for errors determination.

In the framework of the studies performed at Cracow University of Technology it was found that the best solution is not testing of individual components of errors but the designation of systematic and random errors for each points in the measuring machine volume [5].

Virtual machine built in this way requires periodic checks of metrological state of measuring device.

## 5. SUMMARY

Methods presented here allow the determination of coordinate measurements uncertainty. In case of the methods based on comparative measurement the full procedures of uncertainty determination have been developed for coordinate measuring machines.
In case of method using virtual models of machines, the proper model of machine errors have to be determined individually for each machine and accuracy changes of the machine has to be monitored.

In the latter case, it is possible to use this method for other coordinate systems. It needs, however, research under new types of standards that can be used for identification of errors occuring in measuring volume of these devices.

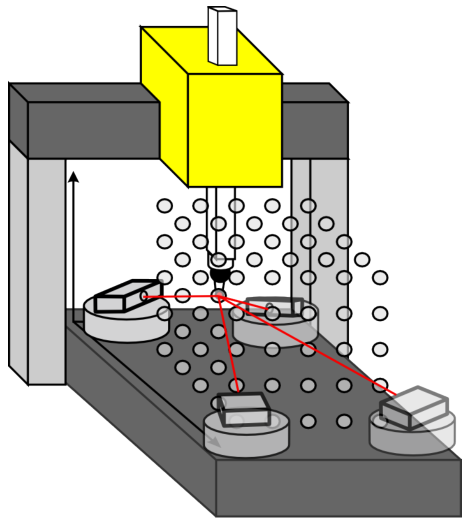

Fig. 2. Determination of errors in CMM measuring volume

## 6. ACKNOWLEDGEMENTS

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