Comments related to ISO 15530 for the evaluation of uncertainty in coordinate measurements

M. Wojtyła[1], W. Płowucha[1], P. Rosner[1]
[1]*University of Bielsko-Biała, Poland,*

Abstract

The introduction of ISO/TS 15530-3 [1] in 2002, its subsequent transformation into a standard [2], as well as the development of ISO/TS 15530-4 [3] and ISO/TS 15530-1 [4], resulted in significant progress in determining the uncertainty of coordinate measurements, which are currently the basic measurement technique for many industries. Experience gained in the meantime shows, however, that in addition to work on new documents, it is advisable to analyse existing documents, e.g. in terms of mutual consistency and compliance with GUM [5-7].

1 Introduction

The basic technique used in geometric measurements in many industries is the coordinate measuring technique, which enables measurements of both dimensions and deviations of form, orientation, position and runout defined in ISO 1101 [1]. A specific feature of coordinate measurements is the fact that the uncertainties of measurements of individual characteristics, performed on the same machine in one measurement cycle, can vary significantly and must be determined separately for each characteristic. Knowledge of measurement uncertainty is particularly important for calibration laboratories and it is mainly for their needs that several versions of simulation software known under the general name of virtual coordinate measuring machine (VCMM or VMM) have been developed.
With the needs of the industry in mind, an experimental method was developed based on multiple measurements of a calibrated object spread over time. For this method, in 2004, ISO/TS 15530-3 was introduced, which was then transformed into the ISO 15530-3 standard [2]. This allowed for a significant increase of interest in determining the uncertainty of coordinate measurements. The

development of ISO/TS 15530-4 [3] and ISO/TS 15530-1 [4] is another important step towards organizing the issue of uncertainty of coordinate measurements.
Carrying out calibrations and measurements for the industry in the framework of an accredited calibration laboratory, and at the same time conducting scientific research and classes with students, the authors often encounter problems to a greater or lesser extent related to documents known under the general name of ISO 15530. Appreciating the importance of standardization in disseminating good practices, this publication presents some problems related to determining the uncertainty of coordinate measurements, which are naturally associated with ISO 15530
In this publication, among others, attention was drawn to some inaccuracies in the aforementioned documents, in particular those related to terminology, mutual consistency and compliance with the GUM [5-7]. The intention of the authors is to provoke a discussion aimed at gathering material enabling further development and improvement of these very important documents. This article is structured as a list of issues that the authors believe may be related to ISO 15530.

2 Substitution and non-substitution measurement

The authors believe that the terms „substitution measurement" ("substitution method") and "non-substitution measurement" in ISO 15530-3 [2] are used unnecessarily and inappropriately. Unnecessarily, because the standard concerns the experimental estimation of the uncertainty of measurements made by any coordinate measuring technique and there is no reason to single out any of them. Moreover, the measurements that have been called "substitution measurement" are too rarely used to be included in the main part of the standard. Anyway, the standard states that substitution measurement is used "especially in the field of gauge calibration". It would be helpful to state that substitution measurement is most often used in the field of gauge calibration.
The justification that these terms are used incorrectly is that what is called "non-substitution measurement" in ISO 15530-3 is ordinary (typical) coordinate measurement, and in the meaning of Guide 99 [8, 2.5] simply "direct measurement method and what is called a "substitution measurement" is a "differential measurement method".
Substitution measurement or more precisely substitution measurement method is a method for eliminating systematic measurement errors caused by errors in the measuring instrument used to compare the quantity being measured with a standard. In the substitution method the value of the quantity being measured is not found directly, from a reading of the measuring instrument, but rather from the magnitude of the standard, which is selected or regulated in such a way that the reading of the measuring instrument remains the same when the quantity being measured is replaced by the standard. For example, weighing an object on a mass comparator, which consists in weighing the reference standard A and the test piece B one after another on the same load carrier according to the weighing cycle A-B-B-A, to eliminate possible linear drifts of the balance. The nominal values of the two standards are identical. The indication of the mass comparator is used only

for determining the difference between the reference standard A and the test weight B (the Borda method) [9]. The substitution method is also extensively used in measuring electrical quantities.

In ISO/TS 15530-1 [4, 6.4 Use of computer simulation] the undefined term „substitution technique" occurs twice in the following sentences: „Computer simulation can be thought of as a virtual substitution technique" and „This is similar to the substitution technique which naturally includes these interactions by performing the actual measurement." In ISO/TS 15530-4 [3] the term "substitution" does not appear.

In the scope of the ISO 15530-3 [2] standard, "substitution measurement" is mentioned in the first paragraph and "non-substitution" is mentioned only in the second: "Non-substitution measurements on CMMs are also covered ...".

In the context of earlier comments regarding the term "substitution", it is worth noting that in some scientific centres this term is used similarly to ISO 15530-3 [2], i.e. as a synonym for „differential measurement", and in others as a synonym for the uncertainty determination technique described in ISO 15530-3. For example, the first situation is related to the statement "The technique is a combination of reversal and substitution techniques and eliminates all systematic geometrical errors ..." [10], and the second one (3 examples): "The overall uncertainty may be evaluated through the substitution method. ..." [11], "... the uncertainty of measurement methods which are usually dedicated to research centres, such as multi-position method and substitution method." [12], "There are different recognized methods for determining the uncertainty of measurements made with CMMs. These include the use of reversal techniques, the substitution method, computer simulation, and expert judgment ..." [13].

3 Compliance with the GUM

In ISO/TS 15530-1 [4] there is a statement: "The techniques presented in the ISO 15530 series are compliant with both ISO 14253-2 and ISO/IEC Guide 98-3 (GUM)".

GUM (JCGM 104) [5] distinguishes two methods of determining uncertainty components (type A and B) and three methods of uncertainty components propagation: analytical, uncertainty budget and Monte Carlo. In addition, it should be remembered that the starting point for determining the measurement uncertainty is defining the measurement model (the measurement model used depends, among others, on the number of uncertainty components) and adopting appropriate probability distributions for individual components. The term „GUM uncertainty framework" used in GUM means the propagation of uncertainty in the form of uncertainty budget implemented with applying the central limit theorem of probability calculus, thanks to which knowledge of probability distributions is not needed. It follows that it is not possible to describe in a few words a specific technique for determining uncertainty.

ISO 14253-2 [14] uses the GUM uncertainty framework.

ISO/TS 15530-1 [4] lists 3 techniques for determining uncertainty: „sensitivity analysis", „use of calibrated workpieces or standards" and „use of computer simulation” (work was also carried out on the fourth technique „use of multiple measurement strategies in measurements of artefacts”) but they are called “techniques to determine task-specific measurement uncertainty components” (why “components”?). It should probably be understood that this classification is not related to the GUM, and the name of the technique attempts to include important elements distinguishing it from others. It is true that „sensitivity analysis” is practically „GUM uncertainty framework” and „use of computer simulation” is in turn „Monte Carlo method”. In the technique called „use of calibrated workpieces or standards” (ISO 15530-3), the propagation of uncertainty components is carried out in accordance with the „GUM uncertainty framework” (i.e. sensitivity analysis), with the main component (u_p) determined by the type A evaluation method.

In ISO 15530-3 [2], the formula for the expanded uncertainty of measurement is given, while the GUM rather gives formulas for the standard uncertainty. This is probably a remnant of an older version of the standard.

4 Uncertainty evaluation technique vs. measurement method

The name of the technique described in ISO 15530-3 [2] „Use of calibrated workpieces or measurement standards” seems appropriate, although it can be shortened to, for example, „Use of calibrated artifacts”. This technique is so far the only one described in detail in a standard. It is a universal technique that can be used not only to evaluate the uncertainty of measurements carried out on classic CMMs, but also with the use of measuring arms, laser-trackers, computed tomography and others, even not necessarily related to the coordinate measuring technique. This technique can be regarded as a reference and recommended for use in the validation of other uncertainty estimation techniques. However, „substitution measurement” understood as differential measurement as well as „use of multiple measurement strategies” or reversal techniques, such as the ball and hole plates calibration procedure, are measurement methods, not techniques for determining uncertainty. Specific techniques for determining measurement uncertainty are developed for them.

5 Measurement model

According to GUM (JCGM 104) [5] the main stages of uncertainty evaluation constitute of formulation and calculation, the latter consisting of propagation and summarizing. An important element of the „formulation” is „developing a measurement model relating the Y to the input quantities, and on the basis of available knowledge, assigning probability distributions”. In the context of this provision, it is worth supplementing ISO 15530-3 with a measurement model. In the current version, according to which the correction of the systematic error is expected, following the example of EA-4/02M [15], it can be written in the form

$$Y = X - b + \delta_{cal} + \delta_w \tag{1}$$

where Y – corrected measurement result, X – CMM indication, b – systematic error (corrected), δ_{cal} – correction for calibrated characteristics of calibrated workpiece, δ_{w} – correction for differences among workpieces and the calibrated workpiece.
The corrections δ_{cal} and δ_{w} are not applied, only the associated uncertainties u_{cal} and u_{w} are taken into account. In the case when the correction of the systematic error b is not expected (and this is the most common situation in industrial conditions), the measurement model has the form

$$Y = X + \delta_{cal} + \delta_{w} \quad (2)$$

In the context of the measurement model, it would be worthwhile to include in ISO/TS 15530-4 [3] at least one example of a measurement model used in some known VCMM software (e.g. such as in [16, Fig. 7] for software developed in PTB). The flow chart model given in [3, Figure B.1] cannot be treated as a measurement model, because it is not possible to derive the uncertainty propagation formula from it. More information on probability distributions would also be useful, especially since CMM geometric errors (except perpendicularity errors) are not just random variables, but functions (see e.g. [17, Fig. 2]). When providing measurement models, it is worth following the example of EA 4/02M [15] - the only document in which models are consistently provided.

6 The problem of systematic error

ISO 15530-3 [2] does not explicitly say that the bias b can be corrected without much difficulty only in exceptional situations, that is, only in relation to dimensions (linear and angular). It should also be remembered that correcting an error requires operator interaction within the part-program – it is necessary to perform an additional operation in the part-program $w = w - b$. This may be enough if it concerns laboratories calibrating artifacts of simple construction, but it is far from sufficient for industrial applications where geometrical tolerances predominate in design drawings (see ISO 1101 [1]).
Correction of the systematic error understood as in ISO 15530-3 [2] in relation to position deviation is theoretically possible but requires major changes in the part-program. For the correction, a value of a certain distance with a sign is needed, while the standard software gives the result in the form of an absolute value. For this reason, the fact that Table A.2 of ISO 15530-3 [2] calculates the value of this error for the position deviation should be considered a significant error. This value cannot be used for correction. Similar and even more difficult cases are other position deviations: concentricity, concentricity and symmetry. Error correction for orientation deviations (parallelism, perpendicularity and angularity) as well as form deviations (straightness, flatness, roundness and cylindricity) is not possible at all.

Safely applying corrections, even with respect to dimensions, requires taking measurements in the exact same place in the CMM space as the experiment and using a standard object of the same shape as the objects being measured. In industrial applications, there is no possibility to correct bias primarily because management systems prohibit unauthorized modification of the approved part program. The presented arguments lead to the conclusion that no corrections should be provided for in the basic version of the standard, which means that the following formula should be used to calculate the uncertainty (symbols according to ISO 15530-3 [2]):

$$u = \sqrt{u_{cal}^2 + u_p^2 + u_w^2 + b^2} \quad (3)$$

or even (then there is no need to use the term „ systematic error” in the standard and calculate *b*):

$$u = \sqrt{u_{cal}^2 + u_p^2 + u_w^2} \quad (4)$$

where u_p is defined differently than in the current standard, namely as

$$u_p = \sqrt{\frac{\sum(y_i - x_{cal})^2}{n-1}} \quad (5)$$

7 Title of ISO/TS 15530-4

Document ISO/TS 15530-4 [3] (Evaluating task-specific measurement uncertainty using simulation) formally deals with “the application of (simulation-based) uncertainty evaluating software (UES) to measurements made with CMMs”, The scope of this document can be easily extended to all uncertainty evaluating software (UES) and not only those where simulations were used to propagate the uncertainty components (Monte Carlo methods).
Furthermore, the document describes testing methods for simulation software.
However, the document does not contain any information on how to determine the measurement uncertainty using the simulation technique, which means that the word „evaluating” is not adequate in the title. After extending the scope, the title of the document may be changed to e.g. „UES Supplier Requirements and UES Testing for CMM”.

8 Task specific uncertainty

In the analysed documents, as well as in the literature, the term "task specific" uncertainty is used, the purpose of which is to emphasize that the measurement uncertainties of different characteristics are different. The authors of this term probably meant not to confuse the term "maximum permissible error", which applies only to the measurement of length, with the term "uncertainty of measurement", which applies to individual characteristics and is related to their definitions.
A similar problem is also known in classical metrology. The uncertainty of measurement with the same micrometre of different dimensions can also be

different, although in this case the reason is usually on the side of the "convenience" of performing the measurement and is visible in repeatability.
According to the authors, after many years of using ISO 15530 [2-4], there is no reason to emphasize, especially in the titles of individual documents, that individual techniques relate to determining "task-specific" uncertainty.

9 Sensitivity analysis

In ISO/TS 15530-1 [4, 6.2], the following statement is outdated: “Since CMMs are complex measuring instruments, directly implementing this technique may only be possible for a limited number of measuring tasks” (we are talking about sensitivity analysis). In many publications, and in particular in [18-20], the opposite has been shown. With appropriate assumptions, the measurement model (of a not too complex form) can include the essence of the coordinate measurements. The sensitivity coefficients present in the uncertainty budgets obtained on the basis of these models allow for an unambiguous indication of the weight of individual components. The mentioned method/technique (called in [18, 19] „sensitivity analysis”) allows to determine the uncertainty for all geometric characteristics, both for linear and angular dimensions, as well as for all geometric deviations (form, orientation, location and runout) [1].

10 Uncertainty associated with the measurement procedure

In ISO 15530-3 [2], the uncertainty component determined as the standard deviation from the results of the u_p experiment is defined as „standard uncertainty associated with the measurement procedure”. The user may have doubts whether it is about the procedure described in the standard or the one used in the part program. Table 3 of this standard lists the 13 different errors that this component covers. Since the standard does not analyse individual errors, it should suffice to generally state that u_p includes errors originating from the CMM, the environment and the person operating the CMM (according to the terminology of ISO 14253-2 [14]: measurement equipment, environment and metrologist).

11 Conclusions

The following remedy is proposed for the situation:

- removal of the terms „substitution measurement” and „non-substitution measurement”
- recognition of the term „substitution technique for determining measurement uncertainty” as a synonym for the term „use of calibrated workpieces or measurement standards”
- deletion of chapter 7 on „substitution measurement” or change of name to „differential measurement”

- recognize that the basic application of the CMM is simple (direct) measurements and give the formula for the uncertainty for the case without correcting for the bias.

The authors appreciate the positive impact of the documents published so far on the dissemination of the practice of determining uncertainty for the most important measurement technique today.The intention of the authors is only to provoke a discussion aimed at gathering material enabling further development and improvement of these very important documents.

References

[1] ISO 1101:2017, Geometrical product specifications (GPS). Geometrical tolerancing. Tolerances of form, orientation, location and run-out

[2] ISO 15530-3:2011, Geometrical product specifications (GPS). Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement. Part 3: Use of calibrated workpieces or measurement standards

[3] ISO/TS 15530-4:2008, Geometrical Product Specifications (GPS). Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement. Part 4: Evaluating task-specific measurement uncertainty using simulation

[4] ISO/TS 15530-1:2013, Geometrical product specifications (GPS). Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement. Part 1: Overview and metrological characteristics

[5] JCGM 104: 2009, Evaluation of measurement data. An introduction to the "Guide to the expression of uncertainty in measurement" and related documents

[6] JCGM 100:2008, Evaluation of measurement data. Guide to the expression of uncertainty in measurement

[7] JCGM 101:2008, Uncertainty of measurement. Part 3: Guide to the expression of uncertainty in measurement (GUM:1995). Supplement 1: Propagation of distributions using a Monte Carlo method

[8] ISO/IEC Guide 99:2007, International vocabulary of metrology. Basic and general concepts and associated terms (VIM)

[9] A. Vâlcu, D. Ştefănescu, About "SI" traceability of micromasses and / or microforces. International Journal of Modern Physics: Conference Series. 24. 2013. DOI: 10.1142/S2010194513600306.

[10] S. Osawa, K. Busch, M. Franke, H. Schwenke, Multiple orientation technique for the calibration of cylindrical workpieces on CMMs. Precision Engineering 29 (2005) 56–64

[11] P. Muller, J. Hiller, Y. Dai, J.L. Andreasen, H.N. Hansen, L. De Chiffre, Estimation of measurement uncertainties in X-ray computed tomography metrology using the substitution method, CIRP Journal of Manufacturing Science and Technology 7 (2014) 222–232

[12] K. Gromczak, K. Ostrowska, D. Owczarek, J. Sładek, Validation of the metrological model of coordinate measuring arm using multifeature check Advances in Science and Technology, Volume 9, No. 28, Dec. 2015, pages 120–124, DOI: 10.12913/22998624/60798

[13] J. Beaman, E. Morse, Experimental evaluation of software estimates of task specific measurement uncertainty for CMMs, Precision Engineering 34 (2010) 28–33
[14] ISO 14253-2:2011 Geometrical product specifications (GPS). Inspection by measurement of workpieces and measuring equipment. Part 2: Guidance for the estimation of uncertainty in GPS measurement, in calibration of measuring equipment and in product verification
[15] EA-4/02M:2015, Expression of the Uncertainty of Measurement in Calibration. European co-operation for Accreditation
[16] E. Trapet, M. Franke, F. Hartig, H. Schwenke, F. Wadele, M. Cox, A. Forbers, et.al., Traceability of coordinate measuring machines according to the method of the Virtual Measuring Machines. Part 2, 1999
[17] D. Heisselmann, M. Franke, K. Rost, K. Wendt, T. Kistner, C. Schwehn Determination of measurement uncertainty by Monte Carlo simulation. Tools in Metrology and Testing XI, 2018 pp. 192-202
[18] W. Płowucha, Point-straight line distance as model for uncertainty evaluation of coordinate measurement, Measurement. 135 (2019) 83–95, https://doi.org/10.1016/j.measurement.2018.11.008.
[19] W. Płowucha, Point-plane distance as model for uncertainty evaluation of coordinate measurement, Metrol. Meas. Syst. 27 (4) (2020) 625–639. https://doi.org/10.24425/mms.2020.134843.
[20] A. Forbes Approximate models of CMM behaviour and point cloud uncertainties. XXIII IMEKO World Congress “Measurement: sparking tomorrow’s smart revolution”, 2021, Yokohama, Japan