PROPOSAL FOR UPDATES IN THE GPS STANDARDS CONCERNING COORDINATE MEASUREMENTS UNCERTAINTY

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Abstract:

The paper presents arguments for and proposals of changes in the series of standards ISO 15530. In particular, authors propose to change the classification of the methods of uncertainty evaluation, change the title of the ISO 15530-4 and make changes that will facilitate the use of these standards to industrial employees. In authors' opinion the classification of the uncertainty evaluation methods for coordinate measurements should be based on the models given in ISO 14253-2 and GUM, i.e. the terms of "black box" and "transparent box" as well as type A and B methods. Authors think that both methods included in ISO 15530-3 and ISO/TS 15530-4 are type A evaluation methods. The measurement model for the evaluation described in the part 3 is classic black box model and the method concerned in part 4 – the transparent box model. The analytical methodology developed by authors (EMU-CMMUncertainty™ software) is accounted as type B evaluation and transparent box model. The reasons of lack of interests for the evaluation method with use of calibrated workpiece are presented. Some simplifications to the procedure as well as extensions to the descriptive part are proposed. It's pointed out that all methods are "task-specific" and all use the uncertainty budget. It is brought to attention that the part 4 applies not only to the simulation but to all methods for which a computer software is provided therefore a proper title change is proposed for this part.

Keywords: uncertainty, coordinate measurements, CMM, geometrical product specification

1. INTRODUCTION

Coordinate metrology is today most important measuring technique for widely understood machine design. It's implemented for measurement of very accurate parts of car and plane engines and gear boxes as well as car bodies or different kinds of sheet metal and plastic parts. Therefore, it's not surprising that intensive standardization works on estimating the uncertainty of this kind measurements are carried out. This measuring technique is also fully compatible with the up-to-date approach to the geometrical product specification [1].

Currently, uncertainty estimation of coordinate measurement is the subject of the ISO 15530 series under a common title *Geometrical Product Specifications (GPS). Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement*. The following documents are available:

- ISO 15530-3:2011 (Part 3: Use of calibrated workpieces or measurement standards) [2] has the status of a standard,
- ISO/TS 15530-4:2008 (Part 4: Evaluating task-specific measurement uncertainty using simulation) [3] – is technical specification.

Others are under development (ISO 15530-1: Overview and general issues) or the work on them is interrupted (ISO 15530-2: Use of multiple measurements strategies in calibration artefacts and ISO 15530-5: Use of expert judgment, sensitivity analysis and error budgeting).

In authors' opinion the problems with finalising the work on the standard arises from assuming wrong classification of the uncertainty evaluation methods. The classification based on the available (used) ways of uncertainty evaluation is and cannot be complete. Moreover, on the very beginning a false thesis was adopted that (quote from the "Introduction" to ISO/TS 15530-4:2008):

> "*For simple measuring devices, this uncertainty can be evaluated by an uncertainty budget according to the recommendations of the Guide to the expression of uncertainty in measurement (GUM). However, in the case of a CMM, the formulation of a classical* ***uncertainty budget*** *is impractical for the majority of the measurement tasks due to the complexity of the measuring process.*"

Anyway, the records in the current documents are in contradiction with the thesis because in ISO 15530-3:2011 (Table 3 — Uncertainty components and their consideration in the uncertainty assessment) one can find **uncertainty budget** consisting of 4 components, and in ISO/TS 15530-4:2008 (subclause 5.5) the following text:

> "*... and the uncertainties from the other influence quantities that have not been taken into account in the UES, which have been evaluated by other appropriate means. These uncertainties shall be combined in a GUM compliant manner.*"

The wording "compliant manner" means here obviously the **uncertainty budget**.

Summarising – the basis of the classification of uncertainty evaluation methods for all kind of measurements should be the measurement model. The number of component uncertainties in the budget arises from the model and in an extreme case can be equal to 1. On the second stage, the classification from the GUM [4] should be considered, i.e. the distinction between type A and type B evaluation. The simulation technique, which is important for coordinate measurements and considered by GUM, should be seen as type A method because the evaluation of a simulation experiment results does not differ from the evaluation of the results of real experiment.

2. CLASSIFICATION OF THE MEASUREMENT MODELS ACCORDING TO ISO 14254-2

The ISO 14253-2 [5] distinguishes to basic models of measurement that serve for evaluation of uncertainty: the *black box model* and the *transparent box model*.

The black box model is a model in which the uncertainties associated with the relevant input quantities are directly represented by their influence on the quantity value being attributed to a measurand. In the black box model it is assumed that the component uncertainties are additive. Because of this assumption, the input quantities should be expressed in the same units as measurand and all sensitivity coefficients are equal to 1.

The transparent box model is a model in which the measurand is obtained by measuring other quantities, which are functionally linked to the value of the measurand. That functional link for simple cases has a form of a function and for complex tasks (such as coordinate measurement) can have a form of an algorithm (computer program).

Other uncertainty evaluation methods can include the elements classified as black box as well as transparent box model because if a black box is "opened" it may turn out that it includes a few smaller black and/or transparent boxes.

3. MODELS OF COORDINATE MEASUREMENTS

The method of uncertainty evaluation "with use of calibrated workpiece" described in ISO 15530-3 is based on the black box model. Almost all components of uncertainty are estimated together, based on a special experiment with the twenty fold measurement of the calibrated workpiece. The direct result consists of 20 values x_i of the analysed characteristic (Fig. 1).

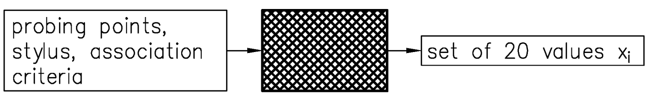

Fig. 1. Model for the method „with use of calibrated workpiece"

The evaluation of the experiment results is limited by small sample size. The final result may be presented as a probability net chart. The standard uncertainty, expanded uncertainty or both can be calculated. In this method almost all uncertainty components are evaluated together in the form of standard uncertainty u_p. Some remarks on the calculation of u_p are presented in section 4.

The method of uncertainty evaluation "with use of simulation" offered by PTB is based on the transparent box model (Fig. 2).

The model consists of the following elements:

- model of propagation of geometrical errors and probing head errors (including information on the design type and parameters of the CMM),
- generators of random numbers of appropriate distributions (a randomly generated vector is added to the coordinates of probing points),
- the association algorithms (the association/fitting algorithms of the CMM evaluation software are used),
- the algorithms for calculation of geometrical characteristics from the associated features (the algorithms of the CMM evaluation software are used).

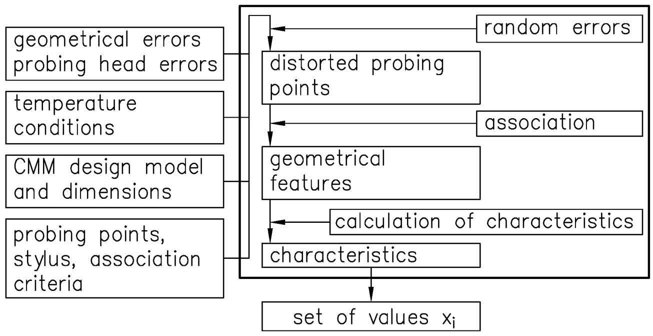

Fig. 2. Model for the PTB simulation software

The input data are:

- the distributions of the geometrical errors and probing head errors identified prior to the simulation software installation (the mean values of the distributions are not necessarily equal to 0; indeed systematic and random errors/components are mentioned),
- environmental conditions (temperature range and gradients),
- actual (measured) coordinates of points of the geometrical elements (features) used to define the analysed characteristic together with the information on the stylus tip used in the measurement and the association/fitting criteria,
- number of simulations (usually significant, $n > 100$).

The direct results of the simulation are:

- the value of the analysed characteristic $\hat{x}$ evaluated in the measurement (this value is known immediately after conducting the measurement),
- values of the analysed characteristic X calculated in simulation runs and treated as the observed values of the random variable $x_1, ..., x_n$.

The evaluation of the results of the simulation experiment can take place differently. The final result may be presented as a histogram, probability distribution, etc. The standard uncertainty, expanded uncertainty or both can be calculated.

The proper statistical evaluation of the results gives the resulting measurement uncertainty. In this method also almost all uncertainty components are evaluated together in the form of standard uncertainty u_{sim}.

At first glance, the method using simulation is not significantly different from the method using the calibrated workpiece. The principle is that:

- the random numbers generators are defined on the basis of previously identified probability distributions of the CMM errors (geometrical errors and probing head errors) – the model of the errors is known,
- in the calculations the CMM software is used – the proper algorithms are known by at least the CMM software developers.

The analytical method of uncertainty evaluation developed by authors [7-10] is also based on transparent box model. It uses practically the same input data as the PTB version of the simulation method. The significant difference is that almost practically all component uncertainties are determined by the type B evaluation.

Fig. 3 depicts the model for very simplified version of the software using only information on the CMM's MPE_E.

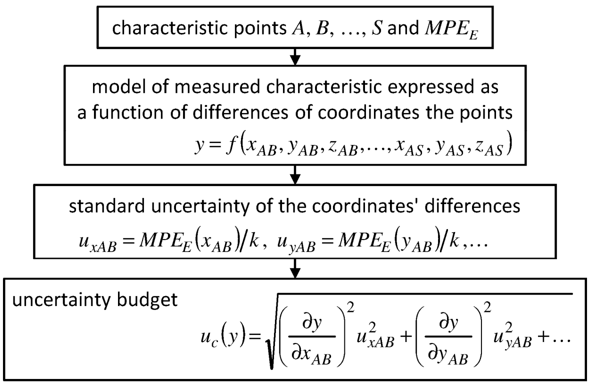

Fig. 3. Model for simpified version of the EMU-CMMUncertainty™ software

4. REMARKS TO ISO 15530-3

In ISO 15530-3 two procedures of uncertainty evaluation are given. First concerns non-substitution measurement and it has strong foundations to be widely used. Second concerns substitution measurements. Due to limited range of its implementation, i.e. calibration of workpieces of simple geometry like e.g. ring and plug gauges, will not be discussed here.

What are currently the obstacles for wide implementation of the standard ISO 15530-3? The user of the standard expects to find there a detailed and unambiguous description of a procedure the result of which will be the uncertainty of measurements carried out on daily basis. Does the 2011 edition of the standard fulfil the condition? In authors' opinion, it does not and the reasons are the following.

4.1. Problem of the "systematic error" b

The result of the statistical evaluation of 20 times repeated measurements is the mean value $\bar{x}$ and the standard deviation s_x. The authors of the standard propose to treat the difference b between the calculated mean value $\bar{x}$ and the calibrated value y_{cal} as the systematic error:

$$b = \bar{x} - y_{cal} \tag{1}$$

and correct the error.

There is no such possibility even for a simplest case which is measurement of a dimension (not speaking of measurements of geometrical deviations). Each measurement is carried out according to previously prepared measuring program and the result is given on an automatically gene-rated report. Nobody will take a risk of neither modifying the measuring program nor making corrections on the measurement report "by hand". Moreover, there is no guarantee that the value of the "systematic error" stays true for a longer period of time. One cannot even exclude that repeated experiment will produce completely different result.

Authors propose a solution similar to the one occurring in the previous edition of the standard. Two cases, described in the following, are to be considered.

Case 1. If the experiment included all factors influencing the uncertainty and the determined uncertainty is not to be used in another uncertainty budget than it is sufficient to determine the expanded uncertainty (there is no need to evaluate the standard uncertainty).

As the expanded uncertainty one can assume e.g.:

- (empirical) 95%-quantile of the variable $\left|X - y_{cal}\right|$,
- k-times the square root of the second central moment of the variable X calculated in respect to the value y_{cal} (and not the mean value $\bar{x}$)

$$U = k \cdot \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_{cal})^2}{n}} \tag{2}$$

- k-times the standard deviation of the values x_i plus the absolute of the "systematic error"

$$U = k \cdot s_x + |b| \tag{3}$$

- value U calculated from the identified (from the 20 measurements) probability distribution of the analysed characteristic from the formula

$$\int_{-U}^{U} f(x)dx = 0.95 \tag{4}$$

Case 2. If the determined uncertainty does not include all influences and is to be a component of uncertainty budget than the standard uncertainty is to be evaluated.

As the standard uncertainty u_p one can assume e.g.:

- square root of the second (empirical) central moment of the variable X calculated in regard to the value of y_{cal} (and not the mean value $\bar{x}$)

$$u_p = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_{cal})^2}{n}} \tag{5}$$

- square root of the second (theoretical) central moment of the variable Y calculated from the identified distribution of the analysed characteristic

$$u_p = \sqrt{\int_{-\infty}^{\infty}(x - y_{cal})^2 f(x)dx} \tag{6}$$

- geometrical sum of the standard deviation of the x_i values and the "systematic error" b

$$u_p = \sqrt{s_x^2 + b^2} \tag{7}$$

The last formula arises from the randomisation of the systematic error by replacing it with the random variable of the binominal distribution. If other distribution is assumed then *b* is introduced to the formula with the coefficient less than 1 (for uniform it's 0,58, for U – 0,78).

Because the systematic error is not to be corrected, the uncertainty budget does not include the component u_b.

4.2. Problem of adding other component uncertainties

In the black box approach there is indeed a possibility to include in the budget other component uncertainties which are not included in the experiment (type A evaluation). The component uncertainties are added in this case with the sensitivity coefficient equal 1. This possibility is, however, conditional on (which should be clearly stated in the standard) identical understanding of all components. There is no doubt that e.g. u_{cal} component can be added to the u_p because both apply to the analyzed characteristic e.g. concentricity. Another aspect is adding components of different nature.

According to ISO 15530-3 the component u_w, determined with type A or B evaluation, can be added to the uncertainty budget. Question is how to determine such component u_w which includes influence of roughness, form deviations, coefficients of thermal expansion (CTE), etc. to be able to add it to the uncertainty budget for coaxiality with the sensitivity coefficient equal 1? It depends on the analysed characteristic. But in the standard one cannot find such limitation.

The formula for u_{wt} given in the standard (designations according to [2])

$$u_{wt} = (T - 20\,°C) \cdot u_\alpha \cdot l \qquad (8)$$

aims to particularly include in the uncertainty budget by type B evaluation **only** (but the standard does not mention that) the component uncertainty arising from the CTEs. Such component is valid only for the analysed characteristic being dimension or position deviation (also some versions of profile any line/surface). It can eventually be assumed (but it also need to be explicitly mentioned in the standard) that for other geometrical deviations (i.e. form, orientation, run-out, and coaxiality or symmetry) the "measured dimension" *l* shall be 0.

If the calibrated workpiece has significantly smaller form deviations and roughness comparing to the regular real workpieces than the budget shall include proper component. The influence of the form deviations and roughness can be evaluated together rather easy in an experiment (type A evaluation). For this purpose, one has to calculate the standard deviation from the results of repeated measurement of the same **real** workpiece (not the calibrated workpiece). Particular measurements shall be carried out with different probing strategies of all geometrical features used for defining the analysed characteristic (including datums). By different probing strategies, the one with the same probing point number but slightly different distribution of the probing points are meant.

5. REMARKS TO ISO/TS 15530-4

Even only by a brief review of the document one can reveal the following inconsistencies or inaccuracies:

- the title of the document (and only of that document) includes wording „task-specific uncertainty" while in regard to coordinate measurement there is no other possibility – all possible evaluation methods can relate only to specific measuring tasks, measurement of particular geometrical characteristics, therefore it should be omitted,
- the title of the document mentions the use of simulation, while inside the document in general uncertainty evaluating software (UES) is discussed. Moreover, in fact, the document relates more to the scope of information, provided by the software supplier (developer), on the software for uncertainty evaluation, i.e. what's included in the title of clause 4: Requirements concerning uncertainty evaluating software, and that should be the title of the standard,
- measurement model presented in [3] (Fig. B.1) does not say anything about the algorithm used in the software. The suplier should provide much more detailed model.

CONCLUSIONS

The standard ISO 15530 needs improvement thanks to which its wide implementation in the industrial conditions will be possible.

The works on the standard should consider the recommendations of ISO 14253-2 and the GUM.

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