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Geometrical product specifications (GPS) — Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement —

Part 3: Use of calibrated workpieces or measurement standards

Spécification géométrique des produits (GPS) — Machines à mesurer tridimensionnelles (MMT): Technique pour la détermination de l'incertitude de mesure —

Partie 3: Utilisation de pièces étalonnées ou d'étalons de mesure

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 15530-3 was prepared by Technical Committee ISO/TC 213, *Dimensional and geometrical product specifications and verification*.

This first edition of ISO 15530-3 cancels and replaces ISO/TS 15530-3:2004, which has been technically revised.

ISO 15530 consists of the following parts, under the general title *Geometrical product specifications (GPS) — Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement*:

— *Part 1: Overview and metrological characteristics* [Technical Specification]

— *Part 3: Use of calibrated workpieces or measurement standards*

— *Part 4: Evaluating task-specific measurement uncertainty using simulation* [Technical Specification]

Introduction

This part of ISO 15530 is a Geometrical Product Specification (GPS) and is to be regarded as a general GPS document (see ISO/TR 14638). It influences chain link 6 of the chain of standards on size, distance, radius, angle, form, orientation, location, run-out and datums.

The ISO/GPS Masterplan given in ISO/TR 14638 gives an overview of the ISO/GPS system of which this standard is a part. The fundamental rules of ISO/GPS given in ISO 8015 apply to this document and the default decision rules given in ISO 14253-1 apply to specifications made in accordance with this document, unless otherwise indicated.

For more detailed information on the relation of this standard to the GPS matrix model, see Annex B.

Coordinate measuring machines (CMMs) have become essential for the verification of geometry in industry. According to the ISO 9000 series of standards, in a quality management system, the relevant measuring equipment is required to be calibrated against certified equipment having a known and valid relationship to internationally or nationally recognized standards in order to establish traceability. According to the *International vocabulary of basic and general terms in metrology* (VIM), a calibration comprises — besides the establishment of the relationship between the measured and the correct values of a quantity — the uncertainty evaluation in the final results (measurands) of the measurement task. However, uncertainty evaluation methods covering the errors arising in the innumerable measurement tasks a CMM can actually perform are often very complex. In these cases, the risk of an unrealistic estimation of task-related uncertainty is likely to arise.

The aim of this part of ISO 15530 is to provide an experimental technique for simplifying the uncertainty evaluation of CMM measurements. In this experimental approach, measurements are carried out in the same way as actual measurements, but with calibrated workpieces or measurement standards of similar dimension and geometry instead of the unknown objects to be measured. The description of this experimental technique to evaluate measurement uncertainty is the key element of this part of ISO 15530. The standardization of such procedures for the uncertainty evaluation serves the worldwide mutual recognition of calibrations and other measurement results.

This part of ISO 15530 is applicable for non-substitution measurement of workpieces or measurement standards, where the measurement result is given by the indication of the CMM. Furthermore, this part of ISO 15530 is applicable for substitution measurement, where, in opposition to the non-substitution measurement, a check standard is used to correct for the systematic errors of the CMM. The latter will generally decrease the measurement uncertainty and is often used, especially in the field of gauge calibration.

This part of ISO 15530 describes one of several methods of uncertainty evaluation, which will be outlined in later ISO documents. Because of the experimental approach, it is simple to perform, and it provides realistic statements of measurement uncertainties.

The limitations of this method can be summarized as: the availability of artefacts with sufficiently defined geometrical characteristics, stability, reasonable costs, and the possibility of being calibrated with sufficiently small uncertainty.

Geometrical product specifications (GPS) — Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement —

Part 3:
Use of calibrated workpieces or measurement standards

1 Scope

This part of ISO 15530 specifies the evaluation of measurement uncertainty for results of measurements obtained by a CMM (coordinate measuring machine) and by using calibrated workpieces or measurement standards. It provides an experimental technique for simplifying the uncertainty evaluation of CMM measurements, whose approach (substitution measurements) leads to measurements being carried out in the same way as actual measurements, but with calibrated workpieces of similar dimension and geometry instead of the unknown workpieces to be measured.

Non-substitution measurements on CMMs are also covered, as are the requirements of the uncertainty evaluation procedure, the measurement equipment needed, and the reverification and interim check of the measurement uncertainty.

NOTE The evaluation of measurement uncertainty is always related to a specific measuring task.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 10360-1:2000, *Geometrical Product Specifications (GPS) — Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 1: Vocabulary*

ISO/IEC Guide 98-3:2008, *Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

ISO/IEC Guide 99:2007, *International vocabulary of metrology — Basic and general concepts and associated terms (VIM)*

ISO 14978:2006, *Geometrical product specification (GPS) — General concepts and requirements for GPS measuring equipment*

3 Terms and definitions

For the purpose of this part of ISO 15530, the terms and definitions given in ISO 10360-1, ISO/IEC Guide 98-3, ISO/IEC Guide 99 and the following apply.

3.1
non-substitution measurement
measurement where the uncorrected indication of the CMM is used as a result

3.2
substitution measurement
measurement where both a workpiece and a check standard are measured in order to provide additional corrections for systematic errors of the CMM

4 Symbols

For the purpose of this part of ISO 15530, the symbols given in Table 1 apply.

Table 1 — Symbols

Symbol	Interpretation
b	Systematic error observed during the evaluation of the measurement uncertainty
Δ_i	Difference between the measured and calibrated values of the check standard when applying the substitution method
k	Coverage factor
l	Measured dimension
n	Number of repeated measurements
T	Average temperature of the workpiece or measurement standard
u_{cal}	Standard uncertainty of the parameter of the calibrated workpiece or measurement standard
u_{p}	Standard uncertainty of the measurement procedure
u_{b}	Standard uncertainty of the systematic error
u_{w}	Standard uncertainty associated with the variations in the uncalibrated workpieces
u_{wp}	Standard uncertainty associated with the variations in the mechanical properties of the uncalibrated workpieces
u_{wt}	Standard uncertainty associated with the variations in the CTEs (thermal expansion coefficients) of the uncalibrated workpieces
u_{α}	Standard uncertainty of the thermal expansion coefficient
U	Expanded measurement uncertainty
U_{cal}	Expanded uncertainty of the calibrated workpiece parameter or measurement standard
x_{cal}	Value of the parameter of the calibrated workpiece or measurement standard
y	Measurement result
y_i	Measurement results during evaluation of measurement uncertainty
y_i^*	Uncorrected indications of the CMM during evaluation of measurement uncertainty when applying the substitution method
$\bar{y}$	Mean value of the measurement result

5 Requirements

5.1 Operating conditions

Before starting the measurements, initialize the CMM and perform procedures such as probe configuration and probe qualification according to the conditions specified in the manufacturer's operating manual. In particular, an adequate thermal equilibrium of the (calibrated) workpiece or measurement standard and the CMM should exist.

For the measurements given in 7.2, the environmental and operational conditions quoted by the CMM manufacturer and conditions quoted in the user's quality manual shall apply. In particular, existing error compensating functions (such as corrections applied via the software of the CMM's computer) shall be active if this is prescribed in the quality manual.

The CMM shall fulfil the specifications of the manufacturer, or — if different — the specifications laid down in the procedural instructions for the measurement task (task-related calibration, see ISO 14978); therefore, it is not necessary to calibrate all the metrological characteristics of a CMM (global calibration, see ISO 14978).

5.2 Similarity conditions

The method requires similarity of the following.

a) The dimension and geometry of the workpiece or measurement standard used in the actual measurements (see 7.2.2) and the calibrated workpiece or measurement standard used in the evaluation of measurement uncertainty (see 7.2.3).

   NOTE Conditions to be repeated are, for example, positions and orientations.

b) The measurement procedure of the evaluation of measurement uncertainty and the actual measurement.

   NOTE Conditions to be repeated are, for example, handling, exchange and clamping, time elapsed between probing points, loading and unloading procedures, measuring force and speed.

c) The environmental conditions (including all variations) during evaluation of measurement uncertainty and actual measurement.

   NOTE Conditions to be repeated are, for example, temperature, temperature stabilization time and temperature corrections (if used).

In Table 2, the similarity requirements are given.

Table 2 — Similarity requirements for workpieces or standard to be measured and the calibrated workpieces or standard used during evaluation of measurement uncertainty

Subject	Requirements	
Dimensional characteristics	Dimensions	Identical within: — 10 % beyond 250 mm — 25 mm below 250 mm
	Angles	Identical within ±5°
Form error and surface texture	Similar due to functional properties	
Material (e.g. thermal expansion, elasticity, hardness)	Similar due to functional properties	
Measuring strategy	Identical	
Probe configuration	Identical	

The similarity of the thermal conditions are considered to be assured if the above requirements are met. The evaluation of measurement uncertainty using the calibrated workpiece shall cover, in particular, the range of temperatures which will prevail during the measurements of the uncalibrated workpieces. If the variation of the thermal expansion coefficient of the measured workpieces or standards is assumed to be significant, this uncertainty contribution has to be taken into account (see 7.3.3 and 7.3.4).

For some CMMs, errors associated with dynamic effects may become significant with a decreasing probe approach distance. For small internal features, e.g. a hole, the probe approach distance may be limited by the feature size. Consequently, care shall be taken to ensure that the probe approach distance is identical.

6 Principle of the uncertainty evaluation using calibrated workpieces

The evaluation of measurement uncertainty is a sequence of measurements, performed in the same way and under the same conditions as the actual measurements. The only difference is that, instead of the workpieces to be measured, one or more calibrated workpieces are measured. The differences between the results obtained by the measurement and the known calibration values of these calibrated workpieces are used to estimate the uncertainty of the measurements.

The uncertainty of the measurement consists of uncertainty contributions

a) due to the measurement procedure,

b) from the calibration of the calibrated workpiece,

c) due to the variations of the measured workpieces (changing form deviations, expansion coefficient and surface texture).

The full effect of all variation in environmental conditions should be included to perform a comprehensive evaluation of the measurement uncertainty.

7 Procedure

7.1 Measuring equipment

The uncertainty evaluation on a CMM using calibrated workpieces requires the following equipment:

a) a task-related stylus set-up;

b) at least one calibrated workpiece.

The metrological characteristics of the calibrated workpieces shall be calibrated with a known and sufficiently low uncertainty to fulfil the requirements of the measurement task.

The probe shall be re-qualified for each calibration.

The uncertainty stated for the calibration of the calibrated workpieces should be valid for the measurement strategy employed during the actual measurements and the uncertainty evaluation, i.e. the measurand of the calibrated workpiece shall be the same as the measurand evaluated in the measurement uncertainty process.

7.2 Execution

7.2.1 General

The user of the CMM has a high degree of freedom to design the measurement procedure (i.e. the measurement strategy) according to the technical requirements. This is possible because the procedure and conditions of actual measurements and those during the uncertainty evaluation shall be the same.

7.2.2 Actual measurement

One cycle of an actual measurement consists of the handling of the workpieces and one or more measurements of the workpieces (see Figure 1).

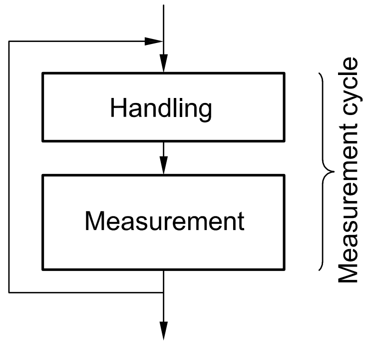

Figure 1 — Procedure of non-substitution measurement — Measurement cycle

The position and the orientation of the measured workpieces are free within the range covered by the uncertainty evaluation.

7.2.3 Uncertainty evaluation

The uncertainty evaluation shall be as follows.

Calibrated workpieces are measured instead of the workpieces. Calibrated workpieces and workpieces shall fulfil the similarity conditions outlined in 5.2. Special loading and unloading procedures shall be performed during the uncertainty evaluation.

To obtain a sufficient number of samples for the uncertainty evaluation, at least 10 measurement cycles and a total of at least 20 measurements on calibrated workpieces shall be carried out. For example, a total of 20 cycles is the minimum, if only one calibrated workpiece per cycle is measured.

During the uncertainty evaluation, the position and orientation of the calibrated workpieces are systematically varied within the limits given by the procedure of the actual measurements.

As specified in 7.2.2, a measurement cycle shall contain all actions involved in a real measurement to ensure the similarity of thermal conditions. This implies, for example, that the CMM has to move through the same positions as if a complete measurement were being carried out, even though during the uncertainty evaluation not all workpieces might be present (dummy measurements).

7.3 Calculation of the uncertainty

7.3.1 General

In a calibration certificate or measurement report, the measurement result, y, and its expanded uncertainty, U, shall be expressed in the form $y \pm U$, where U is determined with a coverage factor $k = 2$ for an approximated coverage probability of 95 %.

When performing the measurements, four uncertainty contributions shall basically be taken into account, described by the following standard uncertainties:

u_{cal} standard uncertainty associated with the uncertainty of the calibration of the calibrated workpiece stated in the calibration certificate;

u_p standard uncertainty associated with the measurement procedure as assessed below;

u_b standard uncertainty associated with the systematic error of the measurement process evaluated using the calibrated workpiece;

u_w standard uncertainty associated with material and manufacturing variations (due to the variation of expansion coefficient, form errors, roughness, elasticity and plasticity).

The expanded measuring uncertainty, U, of any measured parameter is calculated from these standard uncertainties as:

$$U = k \times \sqrt{u_{cal}^2 + u_p^2 + u_b^2 + u_w^2}$$

The coverage factor, k, is recommended to be chosen as $k = 2$ for a coverage probability of 95 %.

In Table 3, the uncertainty contributions for the measurement are listed.

Table 3 — Uncertainty components and their consideration in the uncertainty assessment

Uncertainty component	Method of evaluation (according to the GUM[a])	Designation
Geometrical errors of CMM	A	Assessed in a sum u_p
Temperature of CMM		
Drift of CMM		
Temperature of workpiece		
Systematic errors of probing system		
Repeatability of the CMM		
Scale resolution of the CMM		
Temperature gradients of the CMM		
Random errors of the probing system		
Probe changing uncertainty		
Errors induced by the procedure (clamping, handling, etc.)		
Errors induced by dirt		
Errors induced by the measuring strategy		
Calibration uncertainty of the calibrated workpiece	B	u_{cal}
All the factors contributing to u_p and the thermal environment during the assessment of the calibrated workpiece	B	u_b
Differences among workpieces and the calibrated workpiece in — roughness — form — coefficient of thermal expansion — elasticity	A or B	u_w
NOTE The list of uncertainty contributors may not be exhaustive.		
[a] ISO/IEC Guide 98-3.		

The individual standard uncertainties are evaluated as follows.

7.3.2 Standard uncertainty, u_{cal}, of the calibrated workpiece

The standard uncertainty, u_{cal}, is evaluated from the expanded measuring uncertainty, U_{cal}, and the coverage factor, k, given in the calibration certificate:

$$u_{\text{cal}} = \frac{U_{\text{cal}}}{k}$$

Careful attention should be given to 3.3.2 in the GUM (ISO/IEC Guide 98-3:2008) to ensure that the calibration uncertainty represents the same measurand as used in the measurement. If this is not the case, additional terms of uncertainty shall be considered.

7.3.3 Uncertainty due to the measurement procedure

7.3.3.1 Standard uncertainty, u_{p}, of the measurement procedure

The standard uncertainty, u_{p}, is determined by

$$u_{\text{p}} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(y_i - \bar{y})^2}$$

where

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$$

and n is the number of measurements.

7.3.3.2 Systematic error, b

In most cases a systematic error, b, between the indicated value of the CMM, y_i, and the calibrated value of the calibrated workpiece, x_{cal}, can be observed:

$$b = \bar{y} - x_{\text{cal}}$$

According to the GUM recommendation, measurement results shall be corrected by the amount of systematic effects. In cases where this may not be feasible, the measurement can be expressed by

$$Y = y - b \pm U$$

It is of utmost importance that the single values be listed separately in a calibration certificate.

7.3.3.3 Standard uncertainty, u_{b}, of the systematic error

The value of the systematic error, b, is estimated by the 20 (or more) repeated measurements on the calibrated workpiece. The standard uncertainty associated with b includes the standard uncertainty of the mean value of these measurements. This standard deviation of the mean, a statistical quantity, will be small because of the requirement for a minimum of 20 measurements and is consequently neglected in this evaluation procedure.

However, the standard uncertainty associated with b also includes the effect of the uncertainty in the CTE value for the calibrated workpiece. This quantity is not negligible and shall be included (for CMMs with and without temperature compensation).

In this case, the uncertainty, u_b, is calculated by:

$$u_b = (T - 20\ °C) \times u_\alpha \times l$$

where

u_α is the standard uncertainty of the coefficient of expansion of the calibrated workpiece; this is usually the same as the standard uncertainty of the coefficient of thermal expansion of the workpieces. In the special case in which the calibrated workpiece has also had its CTE calibrated and the CMM used in the measurement evaluation process uses temperature compensation, the u_α term in the formula would be the uncertainty associated with the calibrated CTE value;

T is the average temperature of the calibrated workpiece during the measurement uncertainty evaluation procedure;

l is the measured dimension.

NOTE 1 The formula for u_b is similar to the formula for u_{wt}; this accounts for both the uncertainty in the CTE of the calibrated workpiece and the dispersion of CTEs in the uncalibrated workpieces to be measured.

NOTE 2 The u_b term is necessary for both CMMs that use and do not use temperature compensation. In the former case, this uncertainty represents errors associated with an incorrect thermal expansion compensation. In the latter case, it represents the difference between the CTE of the calibrated workpiece and the centre of the CTE distribution of the uncalibrated workpiece.

7.3.4 Standard uncertainty, u_w, from the manufacturing process

Variations of form errors and roughness due to the changing manufacturing process and variations in elasticity due to changing material and surface properties of the uncalibrated workpieces influence the uncertainty of a measurement. The standard uncertainty, u_{wp}, covers these influences. Note that, using a calibrated workpiece, the above-mentioned uncertainty contributions are partly considered. If multiple calibrated workpieces are used and all measured workpieces correspond in the above-mentioned properties within their required limits, this contribution may be classified as insignificant and can therefore be neglected. Similarly, if the uncalibrated workpieces have negligible variations, then this contribution may be classified as insignificant. If the uncertainty contributions of the manufacturing process cannot be neglected, additional factors have to be considered in u_{wp}. The respective tolerances in form and roughness may serve to assess these contributions.

Additionally, a significant uncertainty contribution results from the variation of the thermal expansion coefficient of the measured workpieces. This quantity, u_{wt}, is calculated by

$$u_{wt} = (T - 20\ °C) \times u_\alpha \times l$$

where

u_α is the standard uncertainty of the expansion coefficient of the workpieces; this can be evaluated from the range of the expansion coefficient which may be delivered by the material supplier;

T is the average temperature of the workpiece during the measurement procedure, expressed in degrees Celsius;

l is the measured dimension.

Then, u_w is calculated as follows:

$$u_w = \sqrt{u_{wt}^2 + u_{wp}^2}$$

7.4 Applying the substitution method: special considerations

In some cases, e.g. gauge calibration, the influence of systematic errors of the CMM may be corrected. For this purpose, the measurement of an additional calibrated working standard is included in the measuring cycle (see Figure 2). By measuring this working standard regularly and comparing the calibrated value of the working standard with the indication of the CMM, a correction value, Δ_i, is derived, which is then applied to the measurement of the workpieces. This procedure is called the substitution method.

The proposed method to assess measurement uncertainty outlined in this part of ISO 15530 is also applicable to the substitution method, but some special considerations have to be taken into account.

— The measurement results, y_i, of the uncertainty evaluation (see 7.3.3.1) have to take into account the corrections, Δ_i, which are applied to the indicated values of the CMM, y_i^*, as follows:

$$y_i = y_i^* + \Delta_i$$

— The uncertainty shall cover the whole measurement procedure. Therefore, the measurement of the working standard and any additional handling shall be included in the uncertainty evaluation.

— The working standard is an intrinsic part of the measurement procedure. Its calibration uncertainty is considered in the experimental procedure. No additional uncertainty contribution need be added.

— The working standard shall not be used as a calibrated workpiece during the uncertainty evaluation. It is necessary to clearly distinguish between the working standard for correction and the calibrated workpiece to analyse the measurement process.

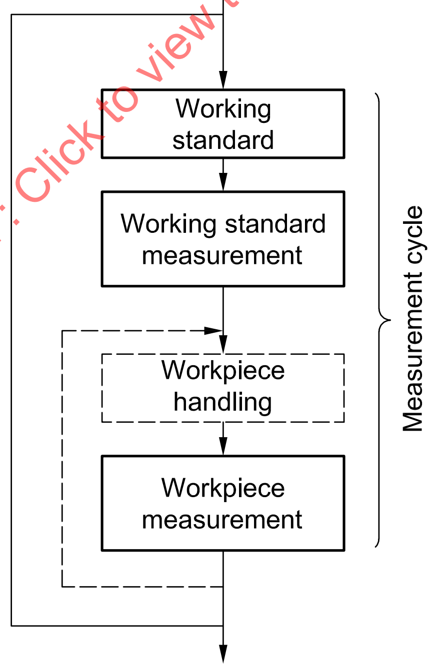

Figure 2 — Procedure of substitution measurement — Measurement cycle

8 Reverification of the measurement uncertainty

The uncertainty evaluation as specified in 7.2.3 should be repeated regularly.

9 Interim check of the measurement uncertainty

The interim check is a simplification of the uncertainty evaluation (see 7.2.3) where calibrated workpieces are substituted in a statistical sampling manner, for the workpieces to be measured. It serves to check whether any assumptions made regarding long period variations in the measuring conditions, in particular the temperature, are still valid. The time intervals between interim checks are specified by the user of the CMM. They are dependent on the required measuring uncertainty and on the environmental conditions.

In an interim check, calibrated workpieces are substituted for the workpieces to be measured in a sampling manner. The deviation between the calibration value for the workpieces and the corresponding measured value from such an interim check shall be smaller than the stated expanded uncertainty, U. If this is not the case, and the reason for this deterioration of the uncertainty cannot be found and remedied, a reverification shall be made.

NOTE This sampling manner means and ensures that over time all positions, orientations and dimensions of the workpieces to be measured will have been checked.

Annex A
(informative)

Examples of application

A.1 Example 1: Measurement of a pump housing

A.1.1 Scenario

For quality assurance, a CMM is integrated in the production line for pump housings. To ensure the quality of the part and to fulfill the requirements of the quality system, the task-specific uncertainties of the most critical measurements performed in the production line have to be known and have to be in an acceptable ratio to the respective tolerance of the part. Figure A.1 shows a simplified drawing of the pump housing.

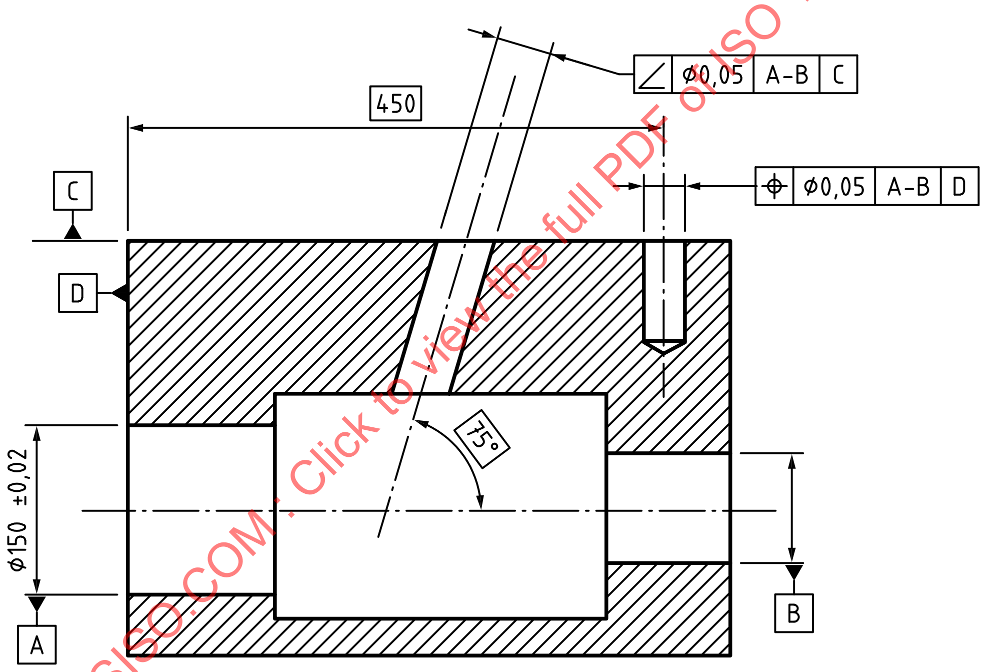

Figure A.1 — Technical drawing of the pump housing (simplified)

A.1.2 Procedure for experimental uncertainty evaluation

The procedure is as follows.

— **Step 1**

One workpiece out of the production series is calibrated with a high precision CMM in a laboratory environment. This can be done, for example, by a service provider, who is capable of stating a valid uncertainty for each measured parameter. The traceabilty of this calibration shall be documented.

The measurement strategy shall reflect as closely as possible the GPS definition of the feature specified in the drawing. In general, this implies a relatively large number of probing points. The result is a calibrated workpiece, where all parameters x_i have stated uncertainties $U_{\text{cal}}(x_i)$.

The calibration certificate for the workpiece is as given in Table A.1.

Table A.1

Parameter	Measurement of:			
	diameter mm	angularity mm	position mm	...
x_i	150,001 5	0,019 6	0,013 8	...
$U_{cal}(x_i)$	0,002 0	0,004 0	0,003 0	...

— **Step 2**

The calibrated workpiece is then measured on the CMM in the production line using the measurement strategy suitable for measurement in production, in general, for economic reasons, a reduced number of probing points.

This measurement is repeated at least 20 times under different conditions (different shifts, different thermal conditions, etc.) in accordance with 5.2. These measurements should ideally also be spread over a longer time period.

The results are collected and evaluated according to the formulae stated in 7.3. Table A.2 shows the results of the experimental uncertainty assessment.

Table A.2 — Results of the experimental uncertainty assessment

No.	Date/time	Operator	Measurement of:			
			diameter mm	angularity mm	position mm	...
1	2003-03-22, 07:33 am	A	150,003 7	0,013 4	0,014 4	...
2	2003-03-22, 08:23 am	A	150,004 3	0,016 4	0,013 4	...
3	2003-03-22, 10:02 am	A	150,003 0	0,017 4	0,014 4	...
4	2003-03-22, 01:55 pm	B	150,002 1	0,020 0	0,013 3	...
5	2003-03-22, 02:13 pm	B	150,003 3	0,018 3	0,015 3	...
6	2003-03-27, 06:08 am	B	150,003 9	0,017 2	0,014 2	...
7	2003-03-27, 07:11 am	B	150,003 2	0,017 4	0,014 4	...
8	2003-03-27, 02:13 pm	A	150,002 7	0,017 4	0,013 4	...
9	2003-03-27, 02:44 pm	A	150,002 5	0,016 9	0,013 9	...
10	2003-03-27, 05:14 pm	A	150,003 2	0,019 3	0,013 3	...
11	2003-03-28, 07:13 am	C	150,002 1	0,016 6	0,014 6	...
12	2003-03-28, 09:02 am	C	150,002 4	0,016 4	0,014 4	...
13	2003-03-28, 09:12 am	C	150,002 4	0,016 3	0,014 3	...
14	2003-03-28, 10:02 am	C	150,003 0	0,017 5	0,014 5	...
15	2003-03-28, 11:32 am	B	150,003 1	0,019 8	0,013 8	...
16	2003-03-28, 02:13 pm	B	150,003 4	0,019 6	0,013 6	...
17	2003-03-28, 03:13 pm	B	150,002 2	0,019 3	0,013 3	...
18	2003-03-28, 03:40 pm	B	150,002 0	0,019 0	0,012 9	...
19	2003-03-28, 04:20 pm	B	150,001 8	0,018 8	0,012 8	...
20	2003-03-28, 06:11 pm	A	150,003 0	0,018 3	0,012 9	...
Calibration uncertainty U_{cal} (see 7.3.2)			0,002 0	0,004 0	0,003 0	...
Standard calibration uncertainty u_{cal} (see 7.3.2)			0,001 0	0,002 0	0,001 5	...
Uncertainty procedure u_p (see 7.3.3.1)			0,000 8	0,001 6	0,000 7	...
Calibrated value x_{cal} (see 7.3.3.2)			150,001 5	0,019 6	0,013 8	...
Mean value $\bar{y}$ (see 7.3.3.1)			150,002 9	0,017 8	0,013 9	...
Systematic error b (see 7.3.3.2)			0,001 4	−0,001 8	0,000 1	...
Uncertainty associated with the systematic error, u_b			0,000 2	0	0,000 5	

— **Step 3**

Finally, the uncertainty contributor, u_w, has to be estimated (see Table A.3). In this example, the calibrated workpiece is deemed representative of the whole production lot with regard to form and surface properties. Therefore, only the possible variation of the expansion coefficient is considered separately.

Table A.3 — Estimation of uncertainty contributor

Workpiece uncertainty contributor	Measurement of:			
	diameter mm	angularity mm	position mm	...
u_{wp}	insignificant	insignificant	insignificant	...
u_{wt}	0,000 2	0	0,000 5	...
u_w	0,000 2	0	0,000 5	...

A.1.3 Resulting uncertainty

The resulting expanded uncertainty is calculated from the formula stated in 7.3.1. It results in the following measurement uncertainties for each contributor (see Table A.4).

Table A.4 — Resulting measurement uncertainties by contributor

Contributor	Measurement of:			
	diameter mm	angularity mm	position mm	...
u_{cal}	0,001 0	0,002 0	0,001 5	...
u_p	0,000 8	0,001 6	0,000 7	...
u_w	0,000 2	0	0,000 5	...
u_b	0,000 2	0	0,000 5	...
U ($k = 2$)	0,003	0,006	0,004	...

These expanded uncertainties are assigned to each corresponding parameter of all workpieces measured. They can, for example, be used for conformance decisions based on ISO 14253-1.

A.1.4 Interim check

Once a week, the calibrated workpiece is substituted for a workpiece to be measured. To validate the stated measurement uncertainty, the calibrated value of the calibrated workpiece is compared with the measured value. The difference shall not exceed the expanded uncertainty, U.

A.2 Example 2: Calibration of ring gauges on a laboratory CMM

A.2.1 Scenario

A calibration laboratory of an automotive company calibrates ring gauges of very similar size in large quantities on a CMM for internal purposes. To reduce systematic errors of the CMM, a calibrated working standard is used in a substitution process (see 7.4): the working standard is stationary, clamped on the CMM, while the gauges to be measured are clamped on an exchangeable pallet. During the procedure, the CMM measures the working standard before and after the measurement of the pallet of ring gauges to be calibrated. The calibrated value of the working standard minus the average of the two observed values of the working standard is added as a correction to the observed value of each gauge on the pallet.

A.2.2 Procedure for experimental uncertainty evaluation

The procedure is as follows.

— **Step 1**

One additional ring gauge is independently calibrated in an accredited laboratory outside the company. This ring gauge is defined as the "calibrated workpiece".

— **Step 2**

After the measurement routines on the CMM have been fully established, one of the regular ring gauges to be calibrated is now replaced by the calibrated workpiece and the whole measurement process (including the substitution measurements on the working standard) is performed 20 times under varying conditions (see 5.2). Each time, a different gauge on the pallet is replaced by the calibrated workpiece.

The correction value determined by the measurements of the working standard is applied to the results of the calibrated workpiece in the same manner as for all other ring gauges.

The results are collected and evaluated according to the formulae specified in 7.3. Table A.5 shows the results.

Table A.5 — Results of the experimental uncertainty assessment

No.	Date/time	Operator	y_i^*	Δ_i	y_i
1	2003-04-22, 07:33 am	A	50,000 3	0,001 1	50,001 4
2	2003-04-22, 08:23 am	A	50,000 5	0,001 3	50,001 8
3	2003-04-22, 10:02 am	A	49,999 8	0,001 5	50,001 3
4	2003-04-22, 01:55 pm	A	49,999 8	0,001 9	50,001 7
5	2003-04-22, 02:13 pm	A	49,999 9	0,001 4	50,001 3
6	2003-04-27, 06:08 am	B	50,000 3	0,001 2	50,001 5
7	2003-04-27, 07:11 am	B	50,001 3	0,000 4	50,001 7
8	2003-04-27, 02:13 pm	A	50,001 1	0,000 6	50,001 7
9	2003-04-27, 02:44 pm	A	50,000 3	0,000 9	50,001 2
10	2003-04-27, 05:14 pm	A	50,000 3	0,001 2	50,001 5
11	2003-04-28, 07:13 am	B	50,000 5	0,001 3	50,001 8
12	2003-04-28, 09:02 am	B	50,000 3	0,001 4	50,001 7
13	2003-04-28, 09:12 am	A	49,999 5	0,001 8	50,001 3
14	2003-04-28, 10:02 am	A	50,000 3	0,001 4	50,001 7
15	2003-04-28, 11:32 am	B	50,000 3	0,001 5	50,001 8
16	2003-04-28, 02:13 pm	B	50,000 7	0,001 5	50,002 2
17	2003-04-28, 03:13 pm	B	50,000 8	0,001 3	50,002 1
18	2003-04-28, 03:40 pm	B	50,000 3	0,001 1	50,001 4
19	2003-04-28, 04:20 pm	B	50,001 1	0,000 2	50,001 3
20	2003-04-28, 06:11 pm	A	50,001 3	0,000 4	50,001 7
Calibration uncertainty U_{cal} (see 7.3.2)					0,000 4
Standard calibration uncertainty u_{cal} (see 7.3.2)					0,000 2
Uncertainty procedure u_p (see 7.3.3.1)					0,000 3
Calibrated value x_{cal} (see 7.3.3.2)					50,001 7
Mean value $\bar{y}$ (see 7.3.3.1)					50,001 6
Systematic error b (see 7.3.3.2)					−0,000 1
Uncertainty associated with the systematic error, u_b					negligable