TECHNICAL SPECIFICATION

ISO/TS 15530-4

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

Part 4: **Evaluating task-specific measurement uncertainty using simulation**

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

Partie 4: Évaluation de l'incertitude de mesure spécifique d'une tâche à l'aide de simulations

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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.

In other circumstances, particularly when there is an urgent market requirement for such documents, a technical committee may decide to publish other types of normative document:

— an ISO Publicly Available Specification (ISO/PAS) represents an agreement between technical experts in an ISO working group and is accepted for publication if it is approved by more than 50 % of the members of the parent committee casting a vote;

— an ISO Technical Specification (ISO/TS) represents an agreement between the members of a technical committee and is accepted for publication if it is approved by 2/3 of the members of the committee casting a vote.

An ISO/PAS or ISO/TS is reviewed after three years in order to decide whether it will be confirmed for a further three years, revised to become an International Standard, or withdrawn. If the ISO/PAS or ISO/TS is confirmed, it is reviewed again after a further three years, at which time it must either be transformed into an International Standard or be withdrawn.

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/TS 15530-4 was prepared by Technical Committee ISO/TC 213, *Dimensional and geometrical product specifications and verification.*

ISO/TS 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 3: Use of calibrated workpieces or standards* [Technical Specification]

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

The following part is under preparation:

— *Part 2: Use of multiple measurements strategies in calibration artefacts* [Technical Specification]

The following part is planned:

— *Part 1: Overview and general issues*

Introduction

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

For more detailed information of the relation of this part of ISO 15530 to the GPS matrix model, see Annex H.

For coordinate measuring machines (CMMs) used to inspect tolerances according to ISO 14253-1, the task-specific uncertainties of measurement are taken into account when tests for conformity/non-conformity are carried out. While knowledge of the uncertainty of measurement is important, up to the present, there have been only a few procedures that allow the task-specific uncertainty of measurement to be stated.

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.

Alternate methods that are consistent with the GUM can be used to determine the task-specific uncertainty of coordinate measurements. One such method that evaluates the uncertainty by numerical simulation of the measuring process allowing for uncertainty influences is described in this part of ISO 15530.

To allow CMM users to easily create uncertainty statements, CMM suppliers and other third party companies have developed uncertainty evaluating software (UES). UES is based on a computer-aided mathematical model of the measuring process. In this model, the measuring process is represented from the measurand to the measurement result, taking important influence quantities into account.

In the simulation, these influences are varied within their possible or assumed range of values (described by probability distributions), and the measuring process is repeatedly simulated, using possible combinations of the influence quantities. The uncertainty is determined from the variation of the final result.

This procedure is compatible with the fundamental principles of the internationally valid *Guide to the expression of uncertainty in measurement (GUM)*. The details of the UES are often hidden in compiled computer code making it difficult for the user to assess the reliability of the calculated uncertainty statements. This part of ISO 15530 sets forth terminology and testing procedures for both the UES supplier and the CMM user to communicate and quantify the capabilities of UES.

This part of ISO 15530 begins by considering the declaration of influence quantities. The declarations identify which influence quantities, along with their ranges of values, the UES can account for in its uncertainty evaluation. For example, some UES can include the effects of using multiple styli during a CMM measurement, while others cannot.

Similarly, some UES can include the effects of spatial temperature gradients or variations of temperature over time, while others cannot. The purpose of the declaration section is to clearly identify to the CMM user what influence quantities, and their ranges of values, the UES will consider in its uncertainty evaluation.

This will allow the user to be able to make informed decisions. Purchasing a UES product with limited capabilities that do not include some influence quantities present during the CMM measurements requires the CMM user to independently evaluate these unaccounted-for influence quantities and combine them appropriately with those that are evaluated by the UES in order to produce a GUM compliant uncertainty statement.

This part of ISO 15530 then goes on to identify four possible methods of testing, recognizing that no single method is comprehensive in a practical sense. For each method, a description is given along with its considerations, advantages and disadvantages. A descriptive example is also included for each method.

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

Part 4: Evaluating task-specific measurement uncertainty using simulation

1 Scope

This part of ISO 15530 specifies requirements (for the manufacturer and the user) for the application of (simulation-based) uncertainty evaluating software (UES) to measurements made with CMMs, and gives informative descriptions of simulation techniques used for evaluating task-specific measurement uncertainty.

Furthermore, it describes testing methods for such simulation software, along with advantages and disadvantages of various testing methods.

Finally, it describes various testing procedures for the evaluation of task specific uncertainty determination by simulation for specific measurement tasks carried out on CMMs, taking into account the measuring device, the environment, the measurement strategy and the object. This document describes the general procedures without restricting the possibilities of the technical realization. Guidelines for verification and evaluation of the simulation package are included.

The document is not aimed at defining new parameters for the general evaluation of the accuracy of CMM measurements.

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

Guide to the expression of uncertainty in measurement (GUM). BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, 1st edition, 1993, corrected and reprinted in 1995

3 Terms and definitions

For the purpose of this document, the terms and definitions given in ISO 10360-1, VIM and GUM apply.

4 Abbreviations

CVE Computer-aided Verification and Evaluation

UES Uncertainty Evaluating Software

NOTE Definitions beyond the words of these abbreviations are not given. The abbreviations and their associated phrases should be meaningful in the contexts of their use in this document.

5 Requirements concerning uncertainty evaluating software (UES)

5.1 Specification of the claimed scope of the UES

The manufacturer of the UES shall explicitly declare the claimed scope of the software. This declaration shall include specifying:

- the types of CMMs for which the software is applicable;
- any CMM accessories allowed;
- which CMM errors are accounted for;
- the considered environmental conditions of both CMM and workpiece;
- the applicable probe types and accessories;
- the associated features included;
- the geometric tolerancing allowed;
- the measuring procedures and strategies covered;
- the operator effects covered;
- any other influence factors affecting the uncertainty of measurement covered by the UES.

In particular, the manufacturer shall specify, by means of the checklist (see Annex A), which uncertainty contributors the software claims to take into account.

NOTE 1 It is expected that the UES account for only some of the influence factors listed here and in Annex A.

NOTE 2 The checklist in Annex A includes the categories listed above.

EXAMPLE 1 An example of UES might take into account:

- the geometrical deviations of the CMM;
- deviations of the probing system;
- influences of temporal and spatial temperature gradients on the workpiece and CMM.

For each influence factor claimed on the checklist of Annex A, the manufacturer shall specify the ranges of validity when applicable. The ranges to be specified include (when claimed) but are not limited to:

a) permissible part spectrum (e.g. exclusion of flexible sheet-metal parts, a minimum arc length for circles, maximum cone apex angles, etc.);

b) permissible task spectrum (e.g. exclusion of scanning or form measurement);

c) permissible temperature range;

d) permissible temporal temperature gradients dT/dt;

e) permissible spatial temperature gradients dT/dx;

f) other permissible environmental conditions.

EXAMPLE 2 If “non 20 °C temperature” is claimed on the checklist, the range of validity might be defined as: Homogenous temperature in space and time, within the limits of 15 °C to 30 °C. This range might also vary depending on the CMM.

5.2 Specification of input to the UES

The UES manufacturer shall specify in detail (or reference appropriate documents that do the same) what input quantities are required to characterize the measurement system and how these quantities are obtained.

NOTE 1 These are the values that are used by the UES to characterize the CMM, the environment, operator effects, etc.

EXAMPLE 1 For example, a requirement of the UES might be to first measure calibrated artefacts in certain positions. The software can then use this information to characterize some of the CMM behaviour.

EXAMPLE 2 Another example of how UES could characterize some of the CMM behaviour could include requiring certain specified MPE values.

EXAMPLE 3 An example of how operator effects might be assessed is from gauge repeatability and reproducibility studies (i.e. GR&R), analysis of variance (i.e. ANOVA), and/or from expert judgment (i.e. “type B evaluation”).

NOTE 2 Any other required information (e.g. the CMM type) is included in this specification requirement.

5.3 Additional UES documentation

The following requirements provide a level of transparency in the fundamental nature of the UES. The manufacturer of the UES shall provide:

— documentation describing how the influence quantities are varied (as a rule, the probability distribution should be documented);

— documentation describing how the uncertainties are derived from the simulated samples;

— documentation describing the essential features of the model.

Transparency of the model increases the user's confidence in the statement of the uncertainty. Documentation of the model and procedure should be sufficient to enable the user to furnish proof of a statement of uncertainty in compliance with this requirement. This is important in particular in connection with ISO 9000, which requires documentation of the procedure used for the uncertainty determination.

5.4 GUM compliance

The manufacturer shall ensure that the statement of the uncertainty complies with the internationally valid principles of the expression of uncertainty (GUM). This includes the statement of a confidence level or a coverage factor.

The combined standard uncertainty may be indicated in addition to the expanded uncertainty.

5.5 Use of results from UES

An uncertainty reported from UES is applicable only as consistent with the scope of the software (5.1). In particular, when using UES, the uncertainty of a measurement shall be composed of the uncertainty evaluated by the UES 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.

NOTE Some informative content dealing with this matter appears in Annex B.

Annex A
(normative)

Checklist — Declaration of influence quantities

No reasonable checklist can be comprehensive. However, this checklist should serve to identify several key influence factors in identifying the scope of uncertainty evaluating software. Varied listings are also included in ISO 15530-1 [1)] and ISO 14253-1. The CMM types listed below are extracted from ISO 10360-1.

Check box	Influence factor	Additional information
	CMM types (see ISO 10360-1)	
	moving bridge	
	fixed bridge	
	column	
	moving table cantilever	
	fixed table cantilever	
	moving ram horizontal arm	
	moving table horizontal arm	
	fixed table horizontal arm	
	L-shaped bridge	
	gantry	
	dual ram	
	CMM accessories	
	rotary table	
	CMM errors	
	rigid-body errors	
	static, nonrigid-body geometry errors	
	dynamic machine geometry errors	
	part loading effects	
	CMM environmental conditions	
	non 20° C temperature	Range:
	thermal compensation applied to CMM	Range:
	spatial gradients	Up to:
	thermal variations in time	Up to:
	algorithm software accuracy	
	hysteresis	
	Probing system accessories	
	multiple styli	Maximum lengths:
	multiple probe	
	articulated probing system	
	styli changing	
	probe changing	

1) Planned.

Check box	Influence factor	Additional information
	Geometric tolerancing	
	datum reference frames	
	form	
	size	
	location	
	orientation	
	orientation with maximum/least material condition	
	position with maximum/least material condition	
	Workpiece environment and conditions	
	non 20° C temperature (same as CMM)	
	non 20° C temperature (independent of CMM)	Range:
	thermal compensation applied to workpiece	
	spatial thermal gradients (e.g. up to 2°C/m)	Up to:
	thermal variations in time (e.g. up to 1°C/hr)	Up to:
	contamination	
	vibration effects	Up to:
	surface roughness	Up to:
	surface waviness	Up to:
	form	Up to:
	fixturing	
	material composition (CTE, etc.)	
	Measuring procedure and strategy	
	sampling strategies	
	number of points	Range:
	location of points on the workpiece coordinate system	Restrictions:
	workpiece location and orientation in the machine coordinate system	
	filtration / outlier removal	
	probing speed	
	probing acceleration	
	Operator effects	
	operator effects (specify)	
	Other effects	
	(specify)	

Probe types (check boxes):

	Discrete point sampling	Offline scanning	Online scanning
contact touch trigger			
contact analog			
noncontact			

Associated features (check boxes):

	Least-squares	Minimum-zone	Maximum-inscribed	Minimum-circumscribed
lines				
circles				
planes				
spheres				
cylinders				
cones				
tori				
splines (specify)				
other (specify)				

Annex B
(informative)

Elements of the uncertainty evaluating software (UES)

B.1 General

The simulation can be integrated into a control and evaluation software of a CMM (on-line) or implemented as an independent system on an external computer (off-line). This document applies to both variants.

B.2 UES Model

The model of the measuring process employed by the UES describes the mathematical relationship between the input quantities (comprised of the measurand and influence quantities) and the output measurement result. The UES does not require that the model be described by a closed mathematical expression. Numerical algorithms, such as the calculation of associated features or filtering of measurement points can, therefore, be included in the model. This makes UES particularly suitable for complex measuring processes like coordinate measurements.

The model used by some UES of the measurement on a CMM can be described by a flow chart, in which the quantities influencing the measuring process are plotted. Figure B.1 shows a typical flow chart.

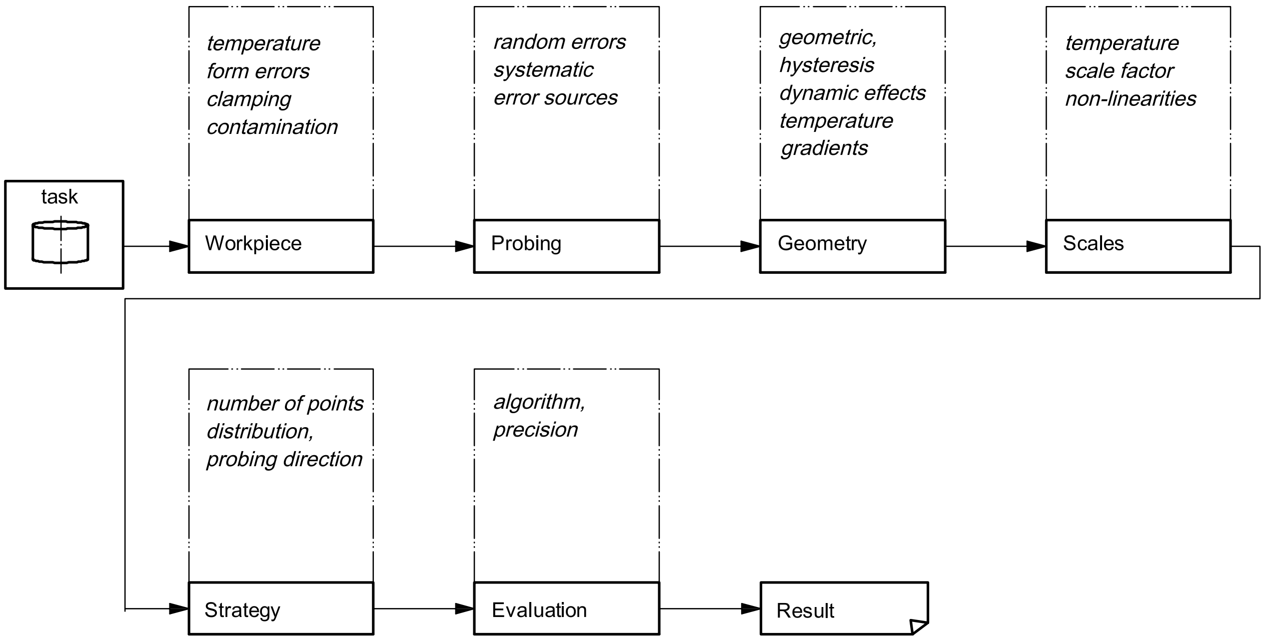


Figure B.1 — Measurement on a CMM represented in the form of a flow chart

Usually not all possible uncertainty influences are taken into account in the model. Influence quantities that have not been considered are to be evaluated by other procedures and added to the total uncertainty (see B.3).

B.3 Determination of the task-specific uncertainty of measurement

The parameters of the simulated measurement, which are important from the metrological point of view, should be as similar as possible to those of the real measurement. The standard uncertainty of a measurement result y is composed of

— the uncertainty u_{sim} determined by the simulation, and

— the uncertainties u_i from the influence quantities that have not been taken into account in the simulation and have been evaluated by other appropriate means.

The combined standard uncertainty, u, is then calculated (assuming the u_i are uncorrelated) by:

$$u = \sqrt{u_{\text{sim}}^2 + \sum u_i^2}$$

With the aid of coverage factors, this standard uncertainty can be brought to the desired confidence level. As a rule, the following is valid:

$$U = 2 \times u$$

for a confidence level of 95 %. If the uncertainty stated by the simulation already is an expanded uncertainty U_{sim}, the simulated uncertainty u_{sim} is to be calculated by division with the appropriate coverage factor.

Annex C
(informative)

Methods of testing uncertainty evaluating software (UES)

C.1 General

The UES shall account for all effects that are specified in the declaration of influence factors according to 5.1. When testing UES, one attempts to verify that, when all influence quantities that are identified in the declaration section are varied within their permitted ranges, the expanded uncertainty calculated by the UES (combined with uncertainty evaluations of other influence factors) contains a large fraction (typically 95 %) of the measurement errors. Given the very large number of significantly different measurands and combinations of influence factors that can occur in CMM measurements, each one of which leads to a particular measurement error that is to be compared to the expanded uncertainty as calculated by the UES, the task of testing UES is enormous.

In an ideal test, for each measurand, all possible permitted influence quantities are varied over their full permitted extent. To illustrate the magnitude of this task, consider the diameter of a cylinder to be the measurand. Ideally, to test the ability of UES for this measurand, one would want to measure a calibrated cylinder on a very large number of metrologically different CMMs, each having a different combination of geometrical and probing errors, and under various thermal conditions, etc. as permitted by the declaration section. On each of these CMMs, one would want to measure many different cylinders having differing aspect ratios and form errors, and for each cylinder one would want to measure in many locations, orientations, with different probes, sampling strategies, etc. For each of these measurements, the observed error would be compared to the UES calculated expanded uncertainty. Obviously this example of a single measurand involves many thousands of measurements on a large number of CMMs and is simply too expensive as a practical test. Thus, testing UES generally consists of some combination of tests involving physical measurements and software measurements.

Thus, comprehensive testing of UES is a generally prohibitively large task. This annex discusses four available methods that could be used to test UES, seeking to be as comprehensive as reasonably possible. No single method of the four discussed below can be practically used as a comprehensive test by itself. Yet, while passing one test may not guarantee always perfect software, failing in a test can be important in revealing problems in the UES. Furthermore, passing the multiple tests described below is more comprehensive than testing and passing one, and thus increases the user's confidence in the software.

These methods are best suited to identify cases when the UES undervalues the uncertainty. It is complicated to assess an overvaluation by the UES, since it is unknown whether a large uncertainty reported by the UES was due to some error or due to a correct use of limited information, which could lead to a larger uncertainty value.

For each method, a description is given along with key considerations and the advantages and disadvantages of the particular testing method. Descriptive examples of each testing method are given in Annexes D to G.

C.2 Physical testing on an individual CMM

C.2.1 General

This technique involves making several measurements using a calibrated artefact in order to statistically compare the observed deviations from the calibrated value with the uncertainties reported by the uncertainty evaluating software. Any object permitted according to 5.1 may be used. The object shall have been calibrated by an independent procedure. In the descriptive example in Annex D, a cylinder is used with a procedure that shows a number of measurement tasks to be evaluated by the UES and which can also be calibrated with sufficient accuracy by independent procedures. For the measurement of such an object, it is recommended to also vary the measurement strategy (position and orientation of the test object, distribution of measurement points) in order to check the influence on the measurement uncertainty stated.

Any object that falls within the claimed scope of the UES could be used and might include gauge blocks, step gauges, ball plates, ball bars, form error standards, and other standards. However any specific object is only suited to a limited extent to test the statements of task-specific uncertainty.

The measurements on the calibrated test objects are carried out on the real CMM for which the uncertainty of measurement is to be determined. The real measurement results, y, are calculated and the related task-specific uncertainties of measurement U are determined by simulation.

Performing a number of measurements on calibrated objects, the coverage of the uncertainty ranges is checked. The plausibility criterion should be satisfied for an appropriate percentage of the time (95 % for $k = 2$); this criterion is that a statement of uncertainty is plausible if:

$$\left| y - y_{\text{cal}} \right| \Big/ \sqrt{U_{\text{cal}}^2 + U^2} \leqslant 1$$

where

y is the measurement result (see Figure C.1);

y_{cal} is the calibrated value (see Figure C.1);

U_{cal} is the expanded uncertainty of calibrated artefact (see Figure C.1);

U is the task specific expanded uncertainty of the measurement (see Figure C.1).

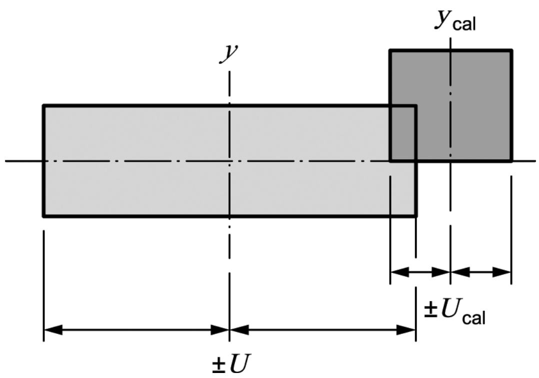


Figure C.1 — Combining uncertainties

A reasonable relationship between the uncertainty of the calibration and the uncertainty of the individual measurement is the goal. As a rule, the following should be valid: $U_{\text{cal}} \ll U$. The higher the calibration uncertainty U_{cal} of the test object, the less meaningful the test.

Here and elsewhere in this part of ISO 15530, whenever U appears (an expanded uncertainty with or without a subscript), a uniform level of confidence is assumed (e.g. 95 %).

C.2.2 Re-testing

Since this method tests the UES in conjunction with a particular CMM, re-testing at regular intervals can be important even if the UES has not been modified. Re-testing is to be carried out:

— when the coordinate measuring machine has been modified;

— when one or several input parameters of the UES model have been changed;

— when, in addition, the environmental conditions have changed beyond the specified range;

— when, for other reasons, there are doubts about the uncertainties determined.

After the first installation on the CMM concerned, short intervals ($\leqslant$ 3 months) should be selected for the re-testing. The positions of the test object in the measurement volume should, if possible, be varied for each intermediate test to guarantee as high a number of independent samples as possible. The intervals may be prolonged when sufficient experience has been gained regarding the stability of the measurements.

C.2.3 Interim check of the input quantities

In the course of the intermediate test it is to be determined to what extent the present state of the CMM complies with the assumptions. The procedure has to state whether or not the evaluation of the influence quantities is still valid. The following influence quantities should in particular be monitored:

— scale factors;

— rectangularities;

— probing errors;

— temperature and temperature gradients.

The input quantities should preferably be monitored by the procedures appropriate in coordinate measurement technology (as in ISO 10360 parts 2-5).

C.2.4 Considerations

Usually the uncertainty evaluating software only reports the uncertainty for some but not all influence factors. The uncertainty of the measurement is actually the combination of the reported uncertainty from the software with evaluations of the uncertainties from other influence quantities, as shown in the equation (assuming the u_i are uncorrelated):

$$u = \sqrt{u_{\text{sim}}^2 + \sum u_i^2}$$

In order not to obscure the validity of the value of u_{sim}, all other quantities, u_i, shall be known to be small in comparison to u_{sim}.

C.2.5 Advantages and disadvantages of the method

The advantages are that:

— this testing matches what the uncertainty evaluating software will actually be used for;

— testing is performed on a real-world CMM, typically the CMM of interest;

— testing includes the gathering of the input data from the machine, so possible mistakes made during that process could be revealed during this testing.

The disadvantages are that:

- physical measurements are time consuming and costly. Several measurements are needed to establish reliable, statistical comparisons. The testing of several combinations of even only a few influence factors can be a very large undertaking;
- testing a wide variety of measurands requires many calibrated artefacts (for example, just using cones one might need a variety of apex angles, sizes, and aspect ratios);
- testing on one CMM does not guarantee that the UES will work on other CMMs, since their error sources might be different.

C.2.6 Descriptive example

See Annex D for a descriptive example.

C.3 Computer-aided verification and evaluation

C.3.1 General

This technique uses computer simulation to test and evaluate the UES. The concept is to simulate a measuring instance based on the claims in the declarations of 5.1. Since the measuring instance is simulated and thus the true value is known in the CVE process, the error of the simulated measurement can be found. The UES produces an uncertainty statement for this measurement and a simple comparison can determine if the error of the simulated measurement is contained within the uncertainty region reported by the software under test. This procedure can be repeated hundreds or thousands of times with varying conditions, and statistics can be determined regarding how often the errors of measurement are contained within their corresponding reported uncertainty ranges.

C.3.2 Explanation of CVE technique

Consider evaluating the uncertainty of a point-to-point length measurement of a gauge block using a given CMM. Uncertainty evaluating software would obviously have to have some knowledge about the performance of the CMM (among other things). But what information about the CMM does the software receive, and how good is the software at using that information?

Some examples of the information used by the UES regarding the performance of the CMM could be (but are not limited to):

- the maximum permissible error, $\mathrm{MPE}_{E,0}$, of an accepted CMM according to ISO 10360-2;
- the above plus $\mathrm{MPE}_{E,0\mathrm{X}}$, $\mathrm{MPE}_{E,0\mathrm{Y}}$, $\mathrm{MPE}_{E,0\mathrm{Z}}$ (specifications of performance measuring along machine axes);
- the above plus the maximum permissible limit, $\mathrm{MPL}_{r,0}$ (a specification of the repeatability of measurements);
- none of the above, but rather a few measurements with calibrated artefacts as specified by the UES;
- none of the above, but rather a large number of measurements with calibrated artefacts as specified by the UES.

Any of these examples is a workable means by which information about the CMM is transferred to the software. It is also clear that these five examples do not all convey the same amount of information about the CMM. This leads to several questions, such as:

- Does the UES gather enough information from the CMM to compute large enough uncertainty values?
- Does gathering only a little information lead to needlessly large uncertainty values?

For instance, a CMM might have a much smaller $\text{MPE}_{E,0X}$ than $\text{MPE}_{E,0}$. When considering measuring the length of a gauge block that is aligned along the X-axis of the CMM, if the UES relies only on $\text{MPE}_{E,0}$, it would likely report a higher value of uncertainty than one that obtained $\text{MPE}_{E,0X}$ as well.

These questions can be answered using a straightforward computer program, as is now described using an illustrative case of measuring the point-to-point length of a gauge block, along with UES that uses option 1) above, the MPE value.

It is possible to emulate some of the common behaviour and error sources of a CMM in a computer program. This emulated CMM can be easily used to produce what an MPE value would be for such a machine. This value can be used as input for the UES. The same emulated CMM program that produced the MPE can be used to determine the error from the gauge block measurement under consideration. One can easily then ask if the error of measurement was within the reported uncertainty. Figure C.2 shows this process as a flow chart. It should be noted that this method depends on the model used, the fidelity of the parameter values, and the selection of the parameters themselves.

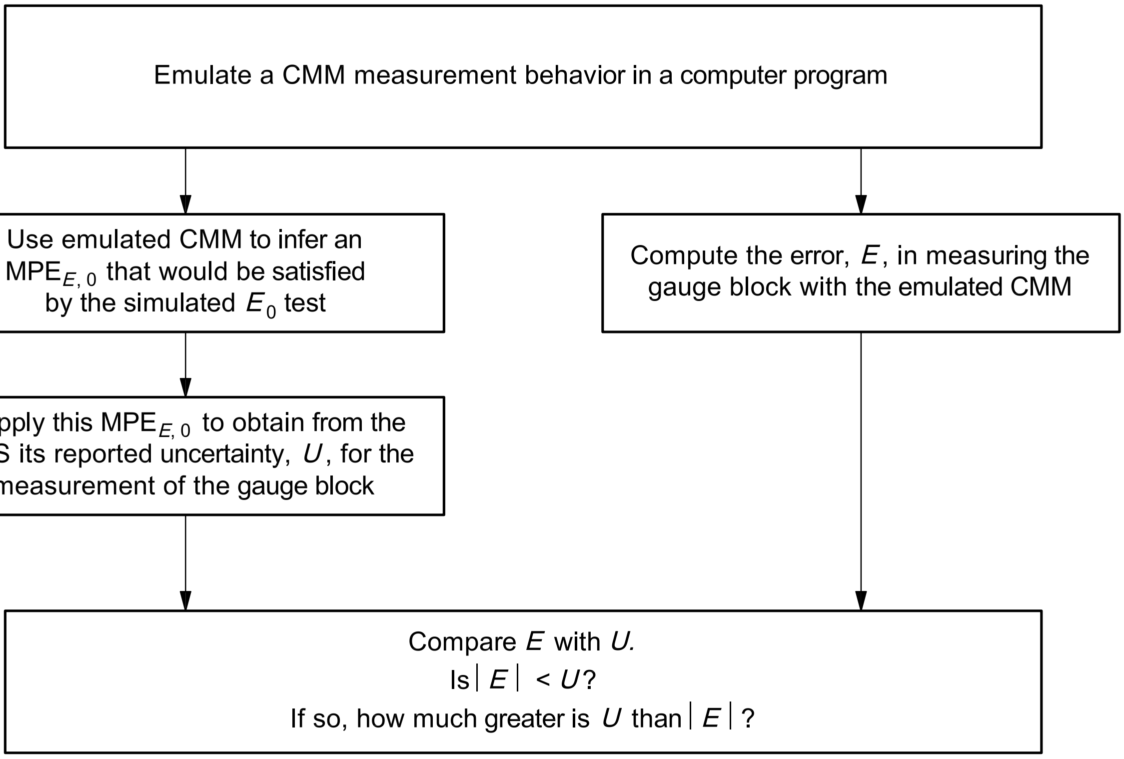


Figure C.2 — A simple CVE flow chart

This straightforward process can be repeated for several measurements using the same emulated CMM. For each iteration, the MPE does not need to be recomputed. The comparison of the absolute error with the expanded uncertainty (in the last step of Figure C.2) should be satisfied for an appropriate percentage of the time (95 % for $k = 2$).

Furthermore, one can use several emulated CMMs to cover much testing of the UES with little effort. A larger flow chart including these iterations is given in the example in Annex E.

The CVE technique is useful, as it can be extended to cover many more cases. This simple case was chosen for clarity of the steps of the method. Extensions can include various geometries, aspect ratios, sampling strategies, locations and orientations, to name a few.

C.3.3 Creation of a simulated measuring instance used in CVE

Creating an emulated CMM in a computer program involves creating error vectors (changes in x, y and z) associated with probing. The error vectors could be programmed to depend on things like the location, probing direction and time. While it is impossible to account for all real world effects in any computer program, there is substantial value in testing with carefully modelled error sources combined with otherwise idealized conditions. For instance, the part being measured could be free of form error in the emulated measurement, while another test could include emulated form errors in a part.

For the purposes of CVE, the declarations of 5.1 determine the limits of what influences can be used to define the error vectors. For instance, if part form errors were included in the declarations section and were emulated, then the error vector associated with a particular probing would depend on the placement of the part in the measuring volume. This allows for testing the software's reported uncertainties without combining them with other uncertainties.

C.3.4 Creation of input quantities

The declarations section includes the indication of the input quantities required by the UES (5.2). These input quantities might arise from measurements of special calibrated artefacts or perhaps from specified MPE values. Appropriate input quantities can be obtained as follows: The emulated CMM created in a computer program can be used to emulate probings of calibrated artefacts or the generation of appropriate MPE values. Thus the input quantities needed by the UES can be obtained.

NOTE These conditions might be different than the ranges given in the checklist (e.g. the input quantities might be measured close to 20 °C, while the software could allow for measurements over a wider temperature range).

To apply the CVE testing, the UES shall have a means to exchange information needed for creation of input quantities. If an MPE value is required by the UES as an input quantity, there has to be means to enter that value. If measurements of certain artefacts are required, then the UES has to be able to exchange information regarding the error vectors that emulate the probings.

C.3.5 Considerations

The technique depends on models — usually a model for a CMM and possibly also models of effects of other influence quantities. The models shall be well understood and shall be consistent with the scope of the influence quantities claimed to be covered by the software under test. While the CVE testing may model fewer influence factors than the UES claims (5.1), it cannot include any that is not claimed.

C.3.6 Advantages and disadvantages of the method

The advantages are that:

— a large number of simulated measurements can be carried out without excessive time and cost;

— a large number of metrologically different CMMs can be simulated and several simulated artefacts can be used without needing explicit separate calibration;

— parameters and influence factors can be isolated and varied with great control allowing the software testing to be specific in its focus;

— it is easy to obtain a quantitative measure of the extent to which a reported uncertainty is under or over valued.

The disadvantages are that:

— well-understood models are readily available for only some influence factors and parameters;

— computer-simulated measurement situations do not include all real world effects (Since certain parameters can be isolated and examined using this method, this can be both an advantage and disadvantage.);

— the method requires some means to exchange information with the software under test.

C.3.7 Descriptive example

See Annex E for a descriptive example.

C.4 Comparison with specific reference results

C.4.1 General

This method involves comparing the reported uncertainty from the software under test with a known reference result. The reference result may be obtained, for instance, from a program written specifically to report the uncertainty under restricted conditions. It is also possible to obtain the reference value from reliable published reference results. Under these conditions, the uncertainty reported by the UES should be no smaller than the reference value (see Figure C.3).

It might also be possible to use another part of the ISO 15530 series to obtain a reference result. However, one shall be aware that such comparisons are complex, since the evaluation of uncertainty is related to available information. For instance, two evaluations can correctly give different uncertainties due to one gathering more information about the CMM than the other. Since both are correct evaluations of the uncertainty, meaningful information from such comparisons is limited and shall be done with care.

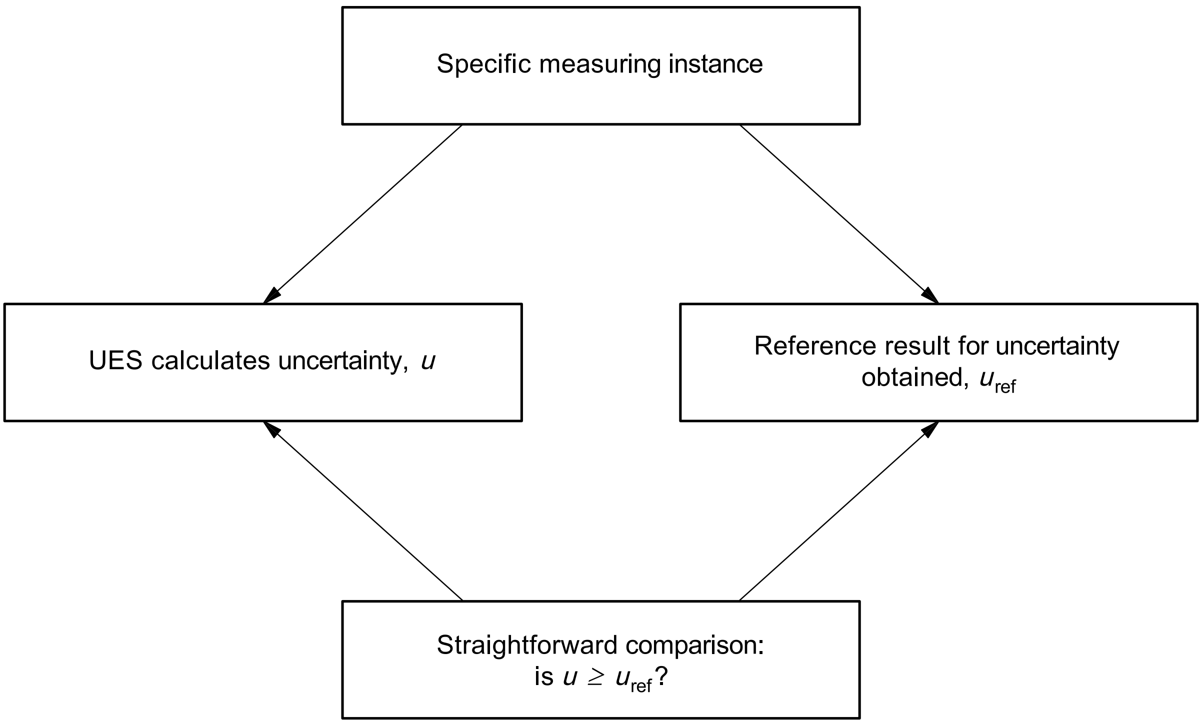


Figure C.3 — A simple diagram of the use of reference values

C.4.2 Considerations

The key consideration of this method is that the reference result shall be known to be correct and to be not larger than necessary due to lack of knowledge. This is possible, for instance, when the conditions are restricted to the point that a reference program is simple enough to be easily verified. In some simple cases, a closed form evaluation might even be possible without the need of software to set a reference value.

An example of a reference program can be seen in evaluating the uncertainty of form, centre location, and diameter when measuring a three-lobed circle with a perfect CMM using n equispaced points (arbitrarily rotated with respect to the lobing). In this example, it is seen that matters are simplified by isolating the component of uncertainty to simply the form of the workpiece. This simplification makes it possible to know a reference result from a simple program created to do just that. This situation is close to reality in cases where the form of a three-lobed part dominates all the CMM errors.

C.4.3 Advantages and disadvantages of method

The advantage is that:

— the comparison is directly between two uncertainty values.

The disadvantage is that:

— the test only applies to very restricted situations covered by the software under test due to the limited availability of reference values.

C.4.4 Descriptive example

See Annex F for a descriptive example.

C.5 Statistical long term investigations

C.5.1 General

This technique involves a compilation of results from a single, well-defined measurement task performed using the software under test over a variety of times, CMMs and conditions. The method is similar to the physical testing of C.2, but consolidates results from measurements made over a broad range of conditions and likely over a long time. So even though this method is partially dependant on C.2, it includes additional benefits. The plausibility criterion of (C.2.1) should be satisfied for an appropriate percentage of the time (95 % for $k = 2$).

As an example, a calibrated check standard might be used daily on a CMM. A history can be kept of the measured value, the calibrated value, the measurement error, and the uncertainty reported by the UES. This history can provide an understanding of the performance of the UES over various conditions through months and years. One could also use such data that spans over several CMMs, which is an advantage of this method.

But the example itself also shows a weakness in the method. If the results of such a long term study indicated that the uncertainty reported by the UES nearly always contained the measurement error, one might conclude that this shall be true for all measurements of similar objects. But if, in fact, the check standard was measured at the same time every day (say in the mornings at start-up) certain environmental conditions for measuring might not be reflected in the long term study. Care shall be taken to document how widely varying the measurement conditions are over the time period of the documented history.

C.5.2 Considerations

The measurement situation shall be well defined and in a way that creates an appropriate category for bundled, comparative results. Care shall be taken to not automatically assume that the large number of measurements necessarily implies a complete coverage of measuring conditions (as in the example in Annex E).

C.5.3 Advantages and disadvantages of method

The advantage is that:

— it allows for testing using a large number of measurements over many parameters.

The disadvantage is that:

— if the measured results are statistically inconsistent with the UES reported uncertainties, it might be difficult to determine the source of the problem due to the variations allowed from measurement to measurement;

— it is probably unusual to have a large amount of historical data except for possibly some very specific measurements.

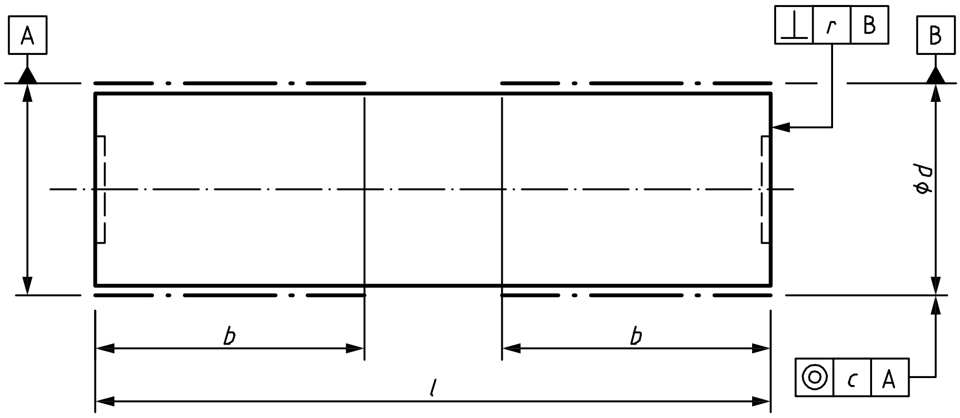
C.5.4 Descriptive example

See Annex G for a descriptive example.

Annex D
(informative)

Descriptive example — Physical testing on an individual CMM

Here, the statement of the uncertainty is checked by a test covering the whole system composed of CMM, CMM software, and UES. The test is based on real measurements performed on a calibrated object. In this example, various measurements are made on a single cylinder (see Figure D.1) in different positions and orientations and with different probe configurations.



Key

l distance of end faces

d diameter of a cylinder

r perpendicularity of the end faces with respect to a cylinder axis

c coaxiality of the cylinder axes

b reference length for the measurement of coaxiality and perpendicularity according to ISO 1101 (no feature)

Figure D.1 — Test cylinder for verification of the simulation

Figure D.2 illustrates that during the test, the test cylinder (shown in Figure D.1) could be placed at various locations and orientations in the measuring volume (positions 1 to 4 are shown in Figure D.1). Furthermore, various measurements could be taken with different probe configurations. A multiple-stylus system is shown, and measurements could be taken with various combinations of styli labelled A, B, and C.

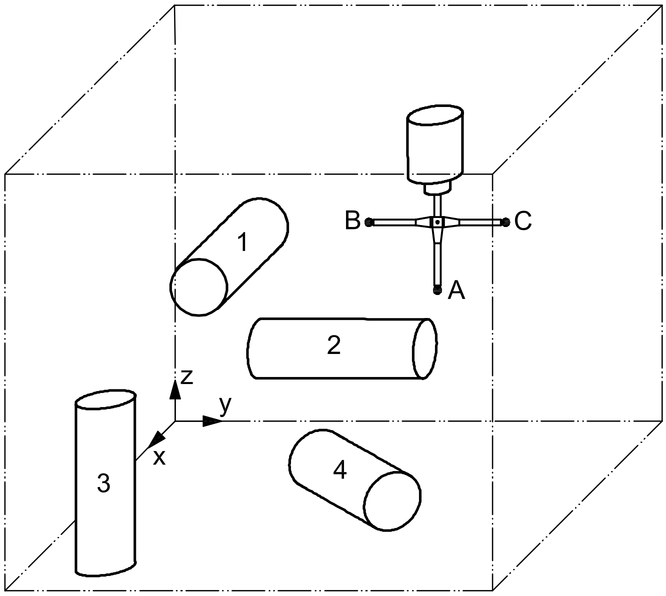


Figure D.2 — Positions of the test cylinder in the measurement volume and probe configurations

Annex E
(informative)

Descriptive example — Computer-aided verification and evaluation

The following flow chart illustrates the use of computer-aided verification and evaluation on a point-to-point length measurement.

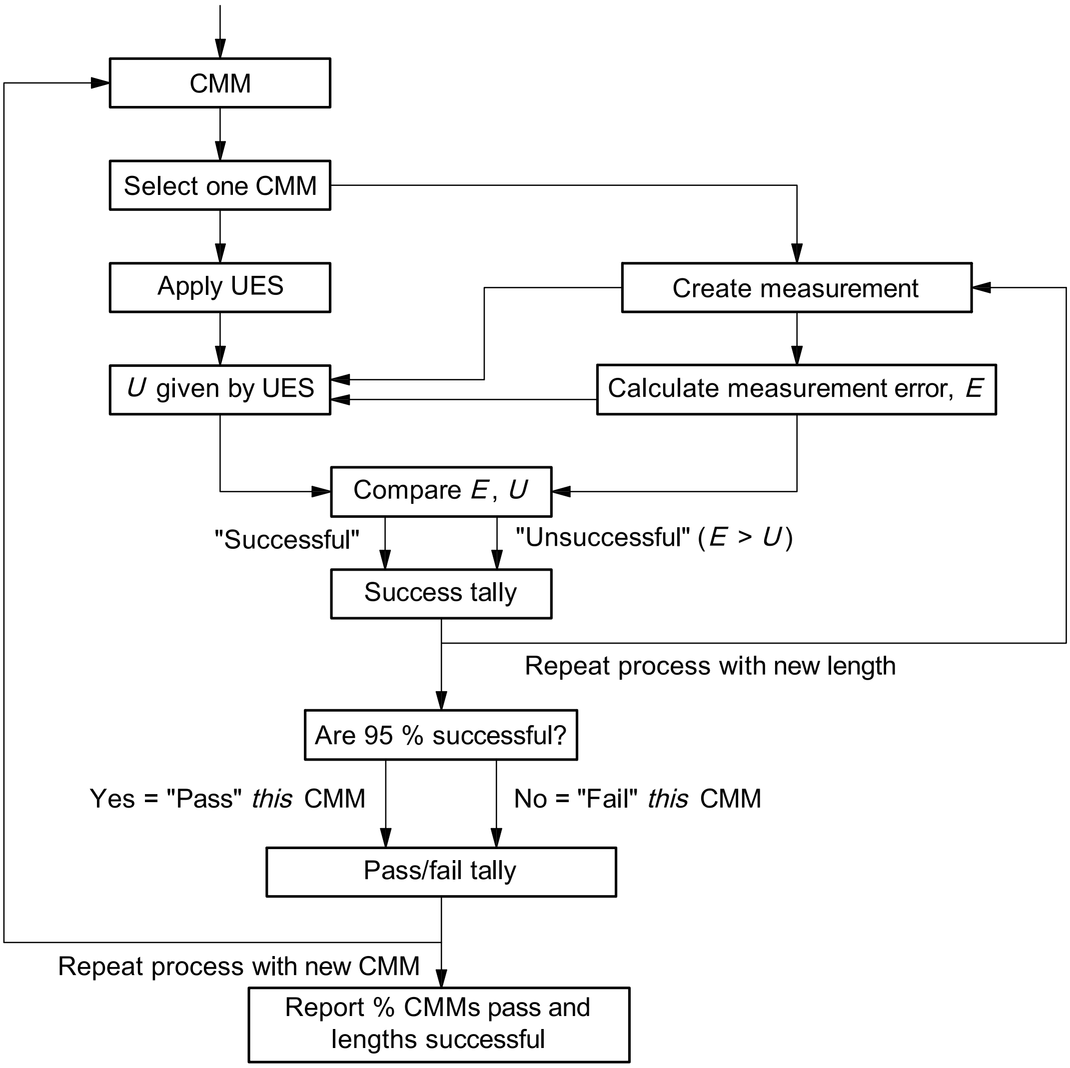


Figure E.1 — Use of CVE on a point-to-point length measuring problem

The flow chart works as follows: given a CMM, or, more accurately, the vector field defining the simulated behaviour of a CMM, two tasks are performed:

— a CMM assessment is made taking into account the simulated behaviour of the CMM (this may involve simulated measurements made to a mathematically generated shape, mimicking a calibrated artefact); and

— a simulated measurement is made taking into account the simulated behaviour of the CMM (again using a mathematically generated length).

Once the CMM has been assessed, and the measurement task is understood, the UES uses this information to report the uncertainty, U. Additionally, the simulated measurement error is computed. This is done by subtracting the true value (known by the mathematical generation of the length) from the measured value (from the simulated measurement, which takes into account the simulated behaviour of the CMM).

Having then the measurement uncertainty reported from the UES, and the corresponding measurement error, one can determine if the magnitude of the measurement error is less than the reported uncertainty. The process can be done repeatedly with other length measurement while a record is kept of the comparisons. The statistics can then be documented as described below, and the whole process can be started again using a different simulated CMM.

CVE results consist of the following information:

— the percentage indicating how often the true value lies within the uncertainty interval given by the UES, e.g. for “good” UES the threshold might be 95 %;

— the average amount of over-valuation of uncertainty, i.e. when the true value is contained within the uncertainty interval, on average how far it is from the nearest uncertainty interval limit;

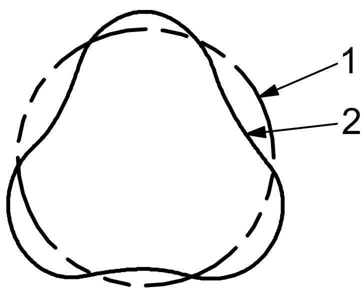
— the average amount of under-valuation of uncertainty, i.e. when the true value is outside the uncertainty interval, on average how far it is from the nearest uncertainty interval limit.

Annex F
(informative)

Descriptive example — Comparison with specific reference results

F.1 General

A simple program can be written to place seven points equispaced about a circle having a 200 mm diameter and having a three-lobed form error of 0,1 mm imposed similar to that shown in Figure F.1. This example considers the measurement of the form using least-squares fitting. The seven equispaced points are rotated randomly with respect to the three-lobed pattern. No other error source besides the form is considered in the measurement.



Key

1 perfect circle

2 three-lobed circle

NOTE The form of the three-lobed circle is exaggerated in size so that its departure from a perfect circle can be seen.

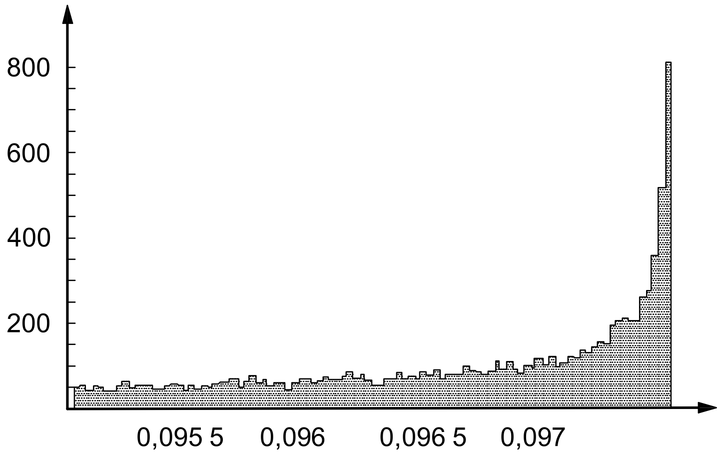
Figure F.1 — A three-lobed form error on a circle

The equation of the lobed form considered in this example is given in polar coordinates by:

$$r = 100 + 0{,}05 \sin(3\theta).$$

F.2 Obtain reference results using a well-evaluated reference program or reliable, published reference results

In this case, the distribution of measured values (resulting from the random, rotational shift of the seven points relative to the lobing) is not a normal distribution (see Figure F.2). The distribution does not even contain the true value, 0,1 mm. The reference result can be described as a combination of a systematic error and a standard deviation or as an interval.



NOTE This histogram is not a normal distribution, and it does not contain the true value of 0,1 mm.

Figure F.2 — Histogram of values of the measured form

Reference results concerning the distribution of errors:

— the smallest interval containing 95 % of measured values is [0,095 3; 0,097 5];

— the smallest interval containing 95 % of errors is [–0,004 7; –0,002 5].

F.3 Obtain the uncertainty value from the same measuring situation from the UES

In this example, the UES reported:

$U(95\ \%) = 0{,}004\ 7$

F.4 Compare results

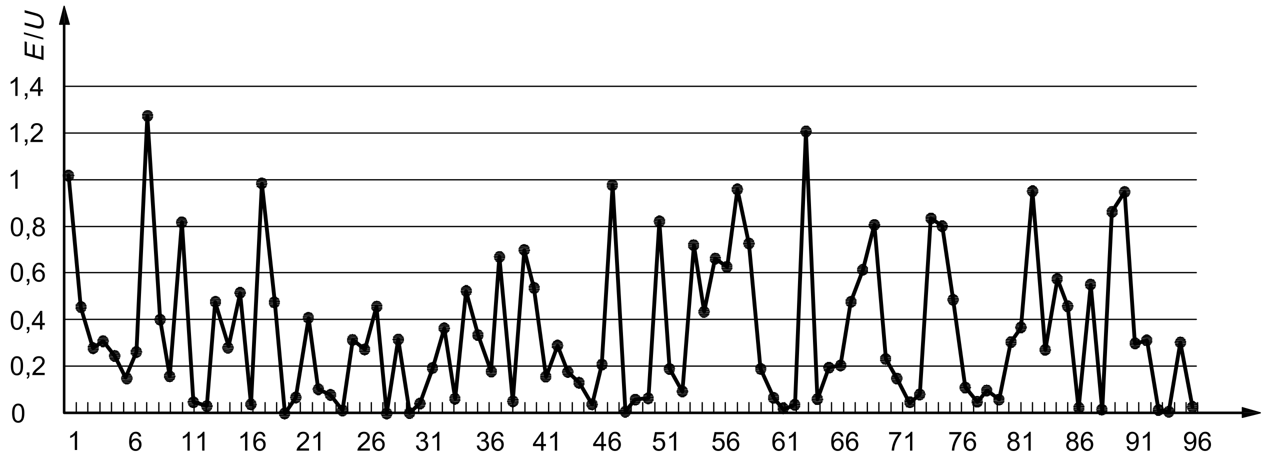
Since 95 % of the measured values are greater than 0,095 3 (from step 1 above), it follows that in 95 % of the cases the true value (0,1 mm) is contained within the interval [measured value $-U$, measured value $+U$]. Thus, the reported value from the UES was consistent with the reference in this case.

Annex G
(informative)

Descriptive example — Statistical long term investigation

A calibrated cylinder is used on a CMM regularly as a check standard. A history is kept of the measured value, the calibrated value, measurement error, and the uncertainty reported by the UES. This history can provide an understanding of the performance of the UES over various conditions through months and years. One could also use such data that spans over several CMMs, which is a strength of the method.

Figure G.1 shows an example of data observed over 100 measurements of the diameter of the cylinder. It is important to note that for each measuring instance a separate U (95 %) is evaluated by the UES. In order to visualize these easily on a single graph, the absolute value of each observed error is divided by the U reported by the UES for that particular measuring instance (indicated E/U in the graph). This data conveys that the uncertainties reported by the UES were sufficiently large in these instances. If, in this example, uncertainty contributions from the influence factors not taken into account by the UES were not combined with the U's reported by the UES, then the results would show even more so that the reported U's are sufficiently large in these instances.



NOTE This historical data shows few points above 1,0, indicating the UES reported sufficiently large uncertainties in these instances.

Figure G.1 — Example of historical data observed over 100 measurements of the diameter of the cylinder

Annex H
(informative)

Relation to the GPS matrix model

H.1 General

For full details about the GPS matrix model, see ISO/TR 14638.

H.2 Information about this part of ISO 15530 and its use

This part of ISO 15530 specifies evaluation of measurement uncertainty for results of measurements obtained by a CMM and by using (simulation-based) uncertainty evaluating software (UES) on measurements made with CMMs, and gives informative descriptions of simulation techniques used for evaluating task-specific measurement uncertainty.

H.3 Position in the GPS matrix model

This part of ISO 15530 is a general GPS document which influences chain link 6 of the chain of standards on size, distance, radius, angle, form, orientation, location, run-out and datums in the general GPS matrix as graphically illustrated in Figure H.1.

Fundamental GPS standards

Global GPS-standards

General GPS-standards

Chain link number	1	2	3	4	5	6
Size						X
Distance						X
Radius						X
Angle						X
Form of a line independent of datum						X
Form of a line dependent of datum						X
Form of a surface independent of datum						X
Form of a surface dependent of datum						X
Orientation						X
Location						X
Circular run-out						X
Total run-out						X
Datums						X
Roughness profile						
Waviness profile						
Primary profile						
Surface imperfections						
Edges						

Figure H.1 — Position in the GPS matrix model

H.4 Related International Standards

The related International Standards are those of the chains of standards indicated in Figure H.1.

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[2] ISO 9000, *Quality management systems — Fundamentals and vocabulary*

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[4] ISO 10360-2:2001 [2)], *Geometrical Product Specifications (GPS) — Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 2: CMMs used for measuring size*

[5] ISO 10360-3:2000, *Geometrical Product Specifications (GPS) — Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 3: CMMs with the axis of a rotary table as the fourth axis*

[6] ISO 10360-4:2000, *Geometrical Product Specifications (GPS) — Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 4: CMMs used in scanning measuring mode*

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[8] ISO 14253-1:1998, *Geometrical Product Specifications (GPS) — Inspection by measurement of workpieces and measuring equipment — Part 1: Decision rules for proving conformance or non-conformance with specifications*

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[10] ISO/IEC Guide 98-3/Suppl. 1 [4)], *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*

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2) Under revision.

3) Under revision.

4) To be published.

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