Importance of the uncertainty in coordinate measurement

The EUCoM project

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EUCoM
Evaluating Uncertainty in Coordinate Measurement

EMPIR EURAMET

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Outline

- Importance of the measurement uncertainty
- Difficulty in coordinate metrology
- State of the art (existing methods)
- The EUCoM project
- Conclusions

What is the uncertainty of measurement

Definition in the VIM (International Vocabulary of Metrology – ISO/IEC Guide 99, § 2.26)

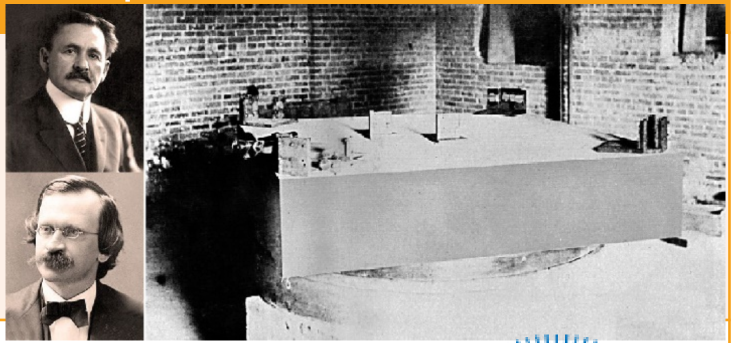
> *non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used*
>
> *…*
>
> *NOTE 2 The parameter may be, for example, a standard deviation called* ***standard measurement uncertainty*** *(or a specified multiple of it), or the half-width of an interval, having a stated* ***coverage probability****.*

The uncertainty expresses the degree of ignorance about a quantity.

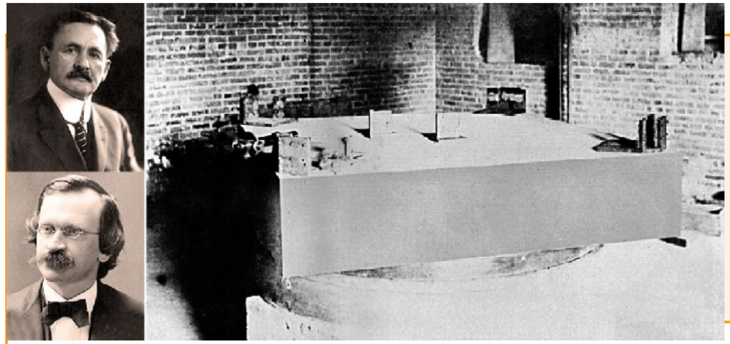
It is based on the “information used” and is then sensitive to how “well informed” who evaluates is

There is no such thing as a “true uncertainty”; the uncertainty is subjective to a fair degree

Why do we measure?

To …	Typical in …	Example
… investigate and know more	science	
… disseminate the metrological traceability	calibration	EA EUROPEAN ACCREDITATION; ilac
… decide based on measurement	inspection	

Why is the uncertainty so important?



In confuting a theory, to be sure that the value really contradicts the theory
In supporting a theory, to know up to which degree
In investigating properties, to let others know how well they have been investigated

To propagate the metrological traceability
To let others know how good a calibration is (e.g. to compare among competing calibration laboratories)
To let others calibrate in turn
To let others decide based on the calibration values

To make informed decisions based on measurement

A parallel between decision making and a distribution chain

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What is the paradigm of an informed decision?

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Typical cases where decisions are needed

- In industry
  - At delivery of supplies to accept and pay
  - Prior to or at delivery of products to verify that they comply with specifications (contracts, regulations, …)
  - After a (critical) production phase to make sure that keeping on is worthwhile (no waste of subsequent production phases)
- In metrological confirmation
  - To approve or reject a measurement instrument (including measurement standards)
- In regulated fields
  - To prove the compliance with regulatory limits (and avoid fines and sanctions)
- In general life
  - To wait or to proceed
  - To choose A or B
  - …

Why is the uncertainty important in decision making?

Measurements values are uncertain by nature, unfortunately

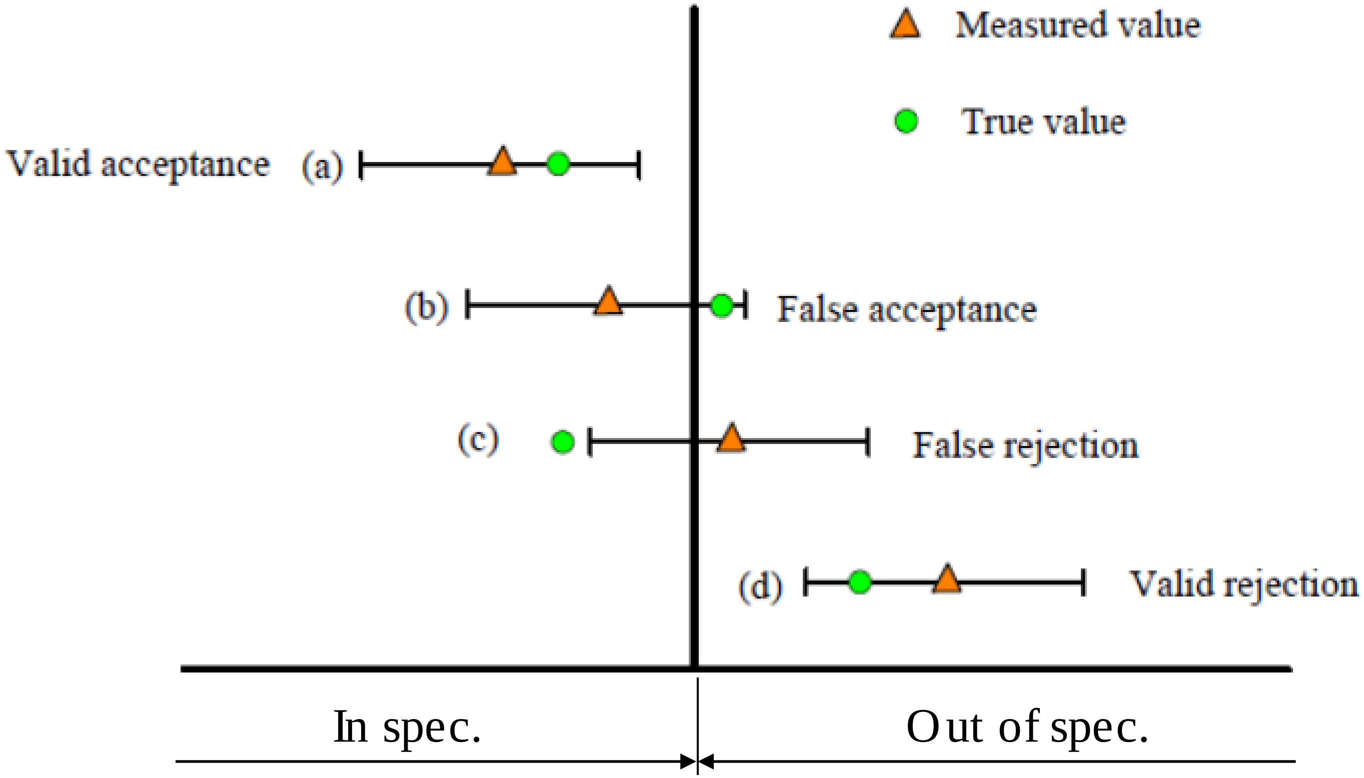
Any decision based on measurement cannot be completely certain

When a decision is needed, an eventual go/no-go is achieved: there is no such thing as a “decision uncertainty”

A risk always exists of wrong decisions

- False acceptance (consumer’s risk)
- False rejection (producer’s risk)

The consequences of false decisions may range from a mild inconvenience to a catastrophic failure

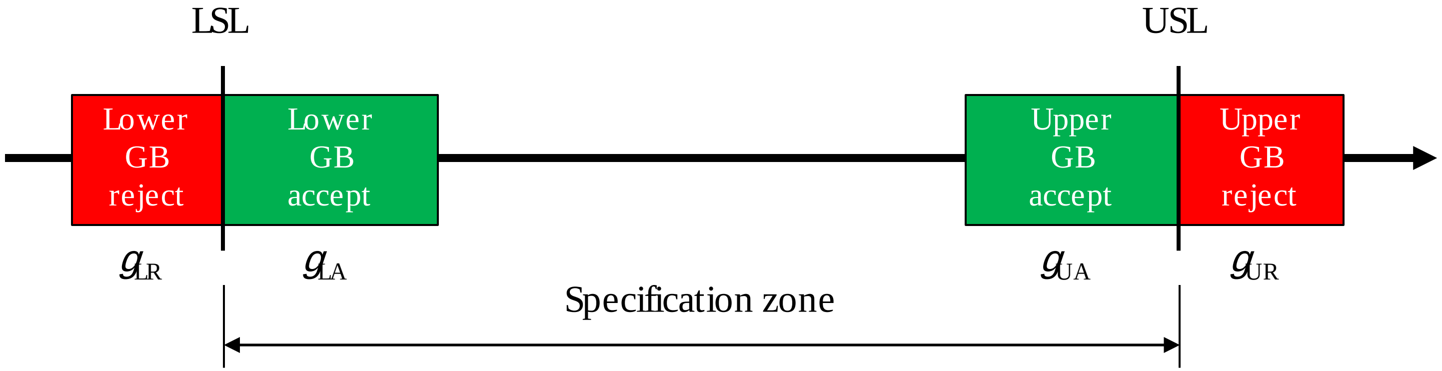


ISO/IEC Guide 98-4 Figure 8

Which countermeasures to minimise the risk of false decisions?

- When the measurement value is far from the specification limits, no problem; when it is close, the risk exists
- As a protection, *guard bands* are established to reduce the acceptance zone
- When a measurement value falls in a guard band, it is not sufficient to verify conformity or nonconformity
- The guard bands are related to the uncertainty; in the common case of a 95 % conformity probability limit and a normal PDF, it holds

$$g = 1.65 \times u \qquad \text{(EN ISO 14253–1)}$$



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The importance of the uncertainty in coordinate measurement is then …

- CMMs are mostly used to verify conformity of parts to specifications (blueprints, CAD), which is subject to decision rules according to the EN ISO 14253–1
- This requires establishing guard bands to protect from false decisions when the measurement values fall close to the specification limits
- The guard bands depend on the conformance probability limit (which sets the maximum accepted risk of false decision) and on the PDF (the most complete description of the uncertainty)
- In common cases of 95 % limit and normal PDF, the standard uncertainty alone is enough to evaluate the guard bands ($g = 1.65 \times u$)

No stated uncertainty (overlooked) ⇒ no guard band ⇒ no protection ⇒ **uncontrolled risk of false decisions**

No compliance with the EN ISO 14253–1

How to evaluate the uncertainty according to the GUM (ISO/IEC Guide 98–3) ?

$$x_1, \cdots, x_n \rightarrow \boxed{y = f(x_1, \cdots, x_n)} \rightarrow y$$

Identify all input quantities (influencing the result)
Describe their joint relation to the result

$$u_1, \cdots, u_n, \; u(ij), \Rightarrow \begin{pmatrix} u_1^2 & \cdots & u(1n) \\ \vdots & \ddots & \vdots \\ u(n1) & \cdots & u_n^2 \end{pmatrix}$$

For each input quantity, evaluate the standard uncertainty u_i (type A or B)
Evaluate possible correlations among input quantity pairs
→ *the correlation ij can be expressed as the covariance ij*
→ *this is equivalent to evaluating a full variance-covariance matrix*

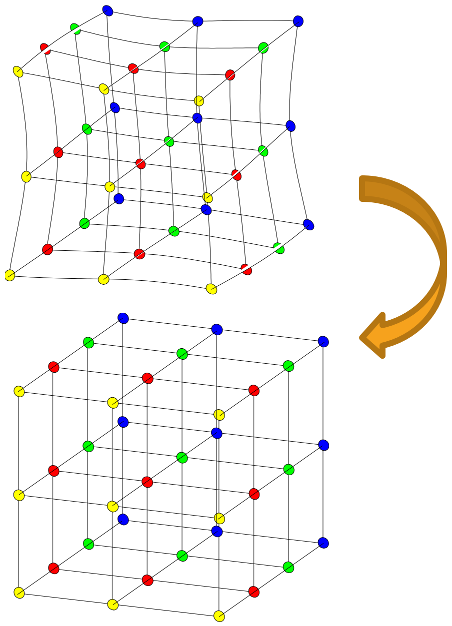
$$\begin{pmatrix} u_1^2 & \cdots & u_{ij}^2 \\ \vdots & \ddots & \vdots \\ u_{ij}^2 & \cdots & u_n^2 \end{pmatrix} \rightarrow \boxed{\begin{matrix} (c_1, \cdots, c_n) \\ \nabla f \end{matrix}} \rightarrow u_y$$

Propagate the input uncertainties and their correlation through the functional relation
→ *sensitivity coefficients needed, derivatives of* f (to form a gradient ∇f)
→ *if there is no correlation, quadratic summation*

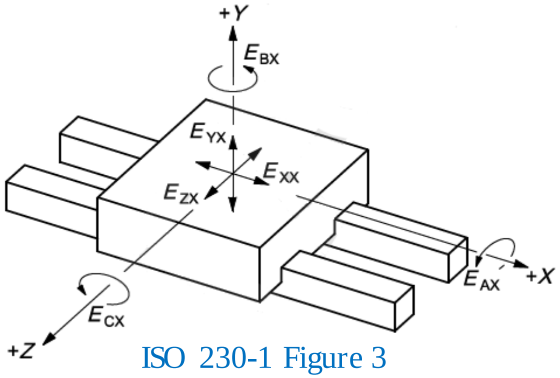
$$U_y = k u_y$$

Evaluate an appropriate coverage factor *k* to achieve a predefined confidence level
Evaluate the expanded uncertainty (coverage interval)

Why evaluating the CMM-related uncertainty is so difficult?
The CMM Geometry errors



$$\boldsymbol{e} = \boldsymbol{t}_x + \boldsymbol{t}_y + \boldsymbol{t}_z + \boldsymbol{r}_x \times \boldsymbol{h}_x + \boldsymbol{r}_y \times \boldsymbol{h}_y + \boldsymbol{r}_z \times \boldsymbol{h}_z$$



ISO 230-1 Figure 3

Error functions (18)

$$\boldsymbol{t}_x = \begin{pmatrix} t_{xx} \\ t_{xy} \\ t_{xz} \end{pmatrix}, \boldsymbol{t}_y = \begin{pmatrix} t_{yx} \\ t_{yy} \\ t_{yz} \end{pmatrix}, \boldsymbol{t}_z = \begin{pmatrix} t_{zx} \\ t_{zy} \\ t_{zz} \end{pmatrix}$$

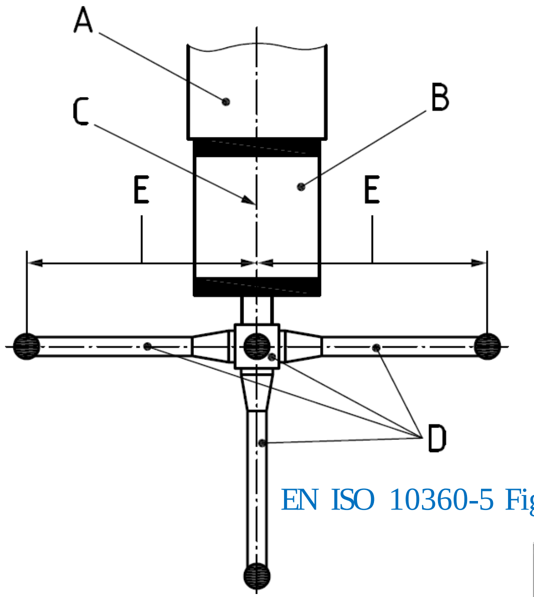
$$\boldsymbol{r}_x = \begin{pmatrix} r_{xx} \\ r_{xy} \\ r_{xz} \end{pmatrix}, \boldsymbol{r}_y = \begin{pmatrix} r_{yx} \\ r_{yy} \\ r_{yz} \end{pmatrix}, \boldsymbol{r}_z = \begin{pmatrix} r_{zx} \\ r_{zy} \\ r_{zz} \end{pmatrix}$$

Effective Abbe arms

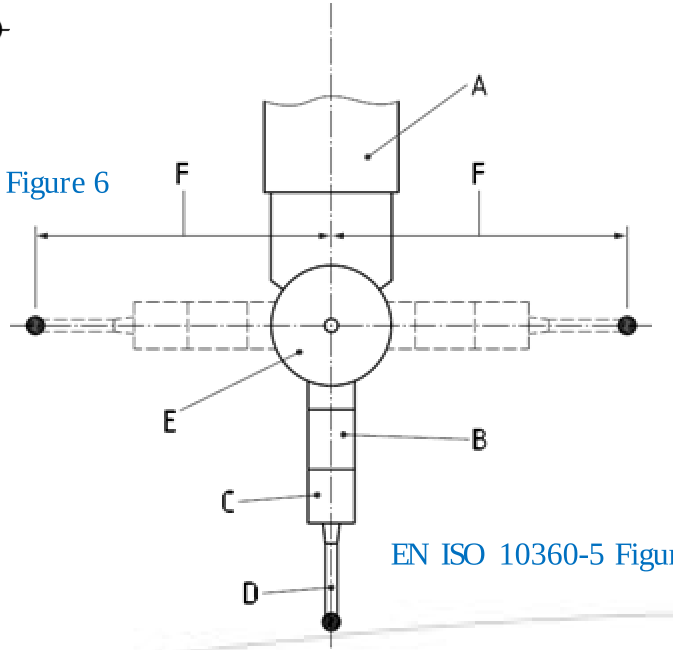
$$\boldsymbol{h}_x = \begin{pmatrix} p_x \\ p_y + s_y \\ p_z + s_z \end{pmatrix}, \boldsymbol{h}_y = \begin{pmatrix} p_x \\ p_y \\ p_z + s_z \end{pmatrix}, \boldsymbol{h}_z = \begin{pmatrix} p_x \\ p_y \\ p_z \end{pmatrix}$$

Each of the 18 error functions is to be parameterised, e.g. in tabular form.
If ~20 parameters per function, then
18 × (~20) = (~360) parameters in total

Why evaluating the CMM-related uncertainty is so difficult? The probing system



EN ISO 10360-5 Figure 6



EN ISO 10360-5 Figure 8

- The probing system is highly reconfigurable to match the specific geometry of the workpieces
- Spatial anisotropy of the response
- Response depending on the stylus length
- In multi-stylus applications (or with articulated probes) the relative offsets of the tips is subject to qualification errors

In summary …

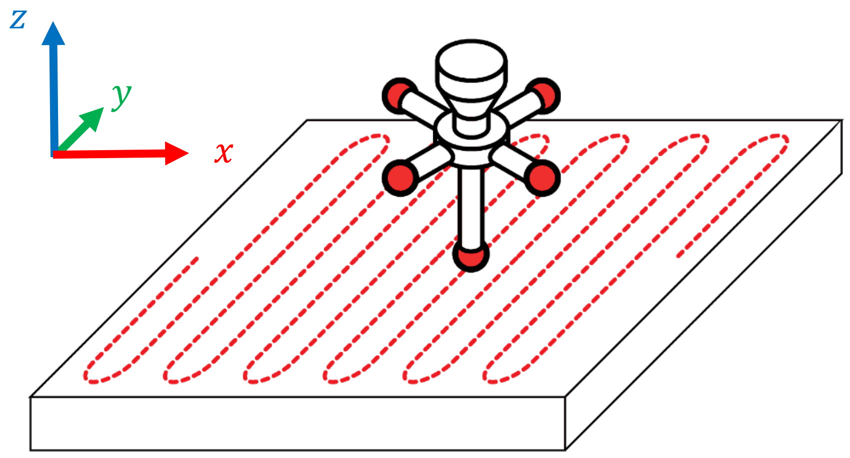
Specification	Sampling	Computing
No (definitional) uncertainty if the specification is unambiguous (very often is not)	• Geometry: The number of input quantities is very high (200+) Usually highly correlated • Probing system Anisotropy Stylus length-dependant response Qualification errors • Temperature Deformation is almost unpredictable Different CMM components react with different time constants, resulting in pulsating behaviours • Workpiece: Form errors ⇔ sampling Roughness	• Versatility: Each measurement can be substantially different from any other • Lack of closed form The measurement model $y = f(x_1, \cdots, x_N)$ is not available, rather iterative algorithms are used Propagation through Jacobian matrices is possible, to be done case by case • Ill-condition Some measurands are intrinsically ill-conditioned The ill-condition can be either reduced (e.g. by proper parameterisation) or amplified (e.g. by bad algorithms)

Available methods for evaluating the CMM-related uncertainty

- GUM mainstream approach (by pen and pencil)
- By use of a very similar calibrated workpiece (EN ISO 15530-3)
- By simulation (e.g. Monte Carlo) methods (ISO/TS 15530-4)

GUM mainstream approach (pen and pencil)

- In a specific measurement task, not all errors may be relevant, and the investigation may focus on the few that are
- For example, in a flatness measurement
  - Single stylus ⇒ no offset issues
  - Single probing direction ⇒ no anisotropy issues
  - No movement in z ⇒ no involvement of the z error functions
  - No squareness involvement
  - Only vertical x and y straightness and the x roll are relevant
- This approach is possible but it requires specific competence
- Difficult to apply for the large public



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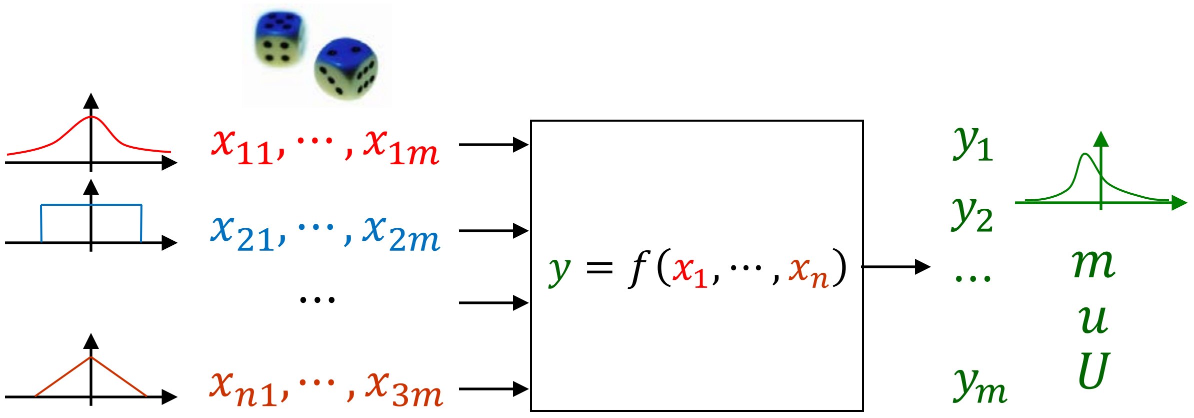
Use of a very similar calibrated workpiece (EN ISO 15530-3)

- For serial (batch) measurements according to a procedure
  - An almost identical (very similar) calibrated workpiece is measured repeatedly when varying the conditions allowed in the procedure
  - The measured errors – known, as calibration values are available – are taken as a representative population, and statistics are derived (standard deviation)
  - Additional terms are added (calibration, temperature, similarity to the real workpiece)
- This is all based on experiment (*a posteriori*, or type A evaluation) and requires a minimum of prior information and expertise ⇒ fit for industry
- It requires extra effort
  - this is somehow acceptable, as the uncertainty evaluation is a separate additional task from measurement, and one can capitalize on this effort all along the series of measurement in the batch
- It requires a very similar calibrated workpiece
  - As many as measurement tasks ⇒ CMM versatility spoiled, cost of maintaining these calibrations
  - Somebody must calibrate the calibrated workpiece, and this includes evaluating the uncertainty ⇒ the problem is not solved rather its burden is moved to somebody else

Simulation (e.g. Monte Carlo) methods (ISO/TS 15530-4)

- Sometimes referred to as *Virtual CMM*
  - The model f is known in software (part programme)
  - The input quantities $x_1, \cdots, x_n$ must be known in their (joined) PDFs
  - m simulated inputs are drawn at random according to their joined PDF
  - A population of simulated results $y_1, \cdots, y_m$ is collected and statistics are derived (e.g. m, u, U)
- Probably the only fully general method (in principle)
- Integration in the CMM software enables delivering the measurement value *and its uncertainty* at the same time
- The derivation of the joint PDF of all input quantities is but trivial and requires specialists (money and time)
- The method requires complex software that only the CMM manufacturer can provide
- A standard cannot and does not intend to illustrate the details, left to competition among CMM manufacturers; it rather proposes a method to verify how well such (black-box) software performs



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Do current standards help in evaluating the uncertainty?

- EN ISO 10360 series deal with acceptance and reverification of CMMs with no coverage of the uncertainty
- Related documents (ISO/TS 23165, ISO/TS 17865) are about the test uncertainty, i.e. the uncertainty incurred when CMMs are *tested* (according to the ISO 10360), which is different from when they are *used* to measure workpieces
- The EN ISO 14253-2 is about evaluating the uncertainty, but with a focus on dimensional measurement in general and no coverage on the CMM specifics

- The EN ISO 15530 is exactly intended to help in evaluating CMM-related uncertainties
  - Part 1 (2013): nice tutorial worth reading but not operative
  - Part 2: (missing) *A posteriori* method. An ISO/TC213/WG10's project run in early 2000's abandoned in 2008 for lack of resources. EUCoM intends to revitalise and finalise that project
  - Part 3 (2011): calibrated workpiece
  - Part 4 (2008): Simulation methods
  - Part 5: (missing) Originally planned on *Expert judgement*, the project never started. EUCoM intends to provide input for a possible new project

The EUCoM project

- EUCoM - *Evaluating the Uncertainty in Coordinate Metrology*
- EMPIR – *European Metrology Programme for Innovation and Research*
- Call *Normative* (research in support of standardisation)
- 2019-06/2021-11, 12 partners from 10 countries (including Japan) + 3 collaborators
- Budget: 706 k€ for 107 man-months
- Even if a research project, intended to directly support the ISO/TC213/WG10 (CMM)

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NMIs

PTB – DE WP3
NPL – GB WP2
TÜBITAK UME – TN
CMI (Czech Metrology Institute) – CZ
Danish Technological Institute – DK
METROSERT – EE
GUM (Główny Urząd Miar) – PL
AIST (National Institute of Advanced Industrial Science and Technology) – JP WKI

Non NMIs

IK4 TEKNIKER – ES WP4
Università degli Studi di Padova – IT
ATH University of Bielsko-Biala – PL

ŠKODA
CZ
Chief stakeholder

Collaborators

ZEISS – DE
PK – PL
MG MARPOSS – IT

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EUCoM objectives

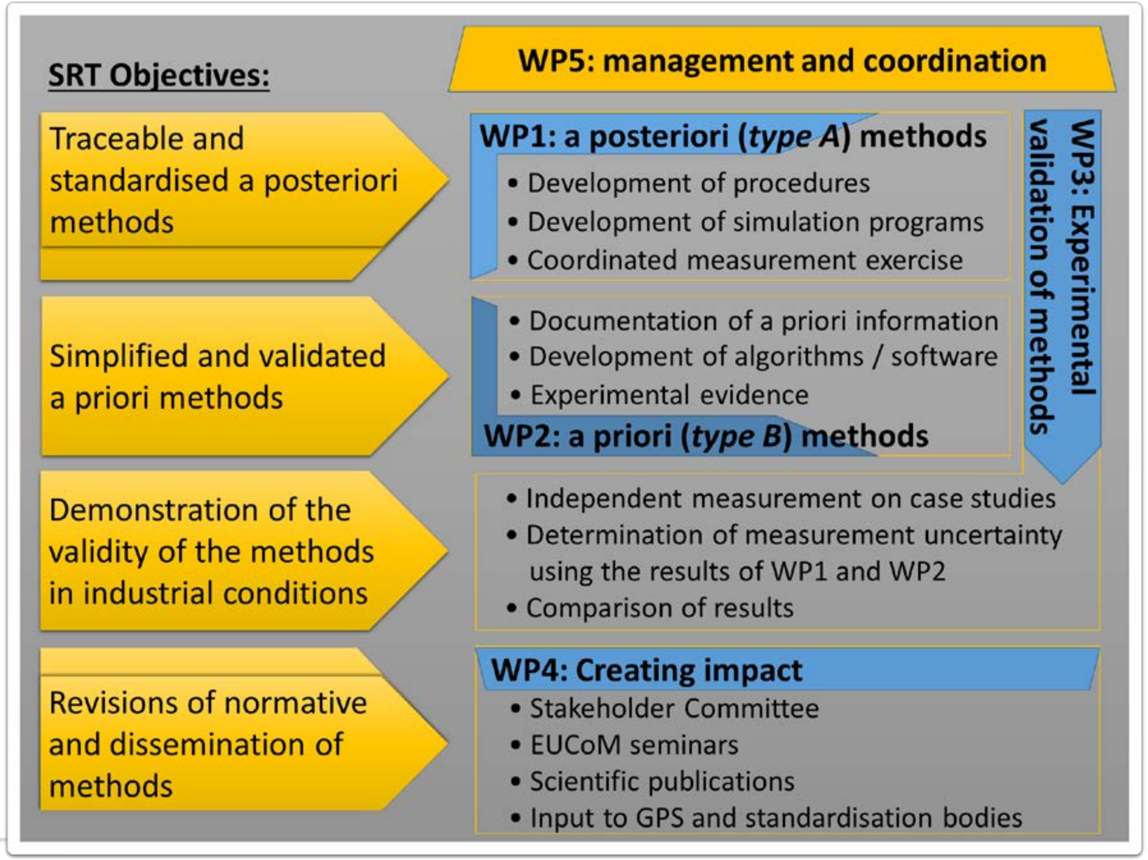
The overall objective of the project is to develop viable methods for evaluating the measurement uncertainty in coordinate measurement in industry, to support the ISO/TC213/WG10 in further development of the ISO 15530 series of standards.

The specific objectives of the project are:

- To develop traceable and standardised methods for evaluating the uncertainty of coordinate measurements a posteriori using type A evaluation (WP1).
- To develop a simplified and validated method for predicting the uncertainty of coordinate measurements a priori using type B evaluation (i.e. expert judgement) (WP2).
- To demonstrate the validity of existing methods and those from objective 1 & 2 in industrial conditions and evaluate their consistency and accuracy against the Guide to the Expression of Uncertainty in Measurement (GUM) and its supplements (WP3).
- To contribute to revisions of EN ISO 15530 series and EN ISO 14253-2 by providing the necessary data, methods, guidelines and recommendations, in a form that can be incorporated into the standards at the earliest opportunity. In addition, to collaborate with the technical committees CEN/TC290 and ISO/TC213/WG10 and the users of the standards they develop to ensure that the outputs of the project are aligned with their needs and recommendations for incorporation of this information into future standards at the earliest opportunity. To promote early dissemination of the developed methods to industry (WP4).

Objectives and WPs

- *A posteriori* method
  - type A evaluation
  - Based on ISO/WD 15530-2 (abandoned)
  - Similar to ISO 15530-3 but with no calibrated artefacts
- *A priori* method
  - type B evaluation
  - Originally planned as ISO 15530-5 (never started)
  - Useful for prediction
  - An alternative method emerged from ATH as a further option
- Validation
  - All partners involved in experimental validation
  - Extensive campaign



Current state of the project and conclusions

- The initial three-year timeframe 2018-06/2021-05 extended to 2021-11 to recover (partly) the delays induced by the COVID-19 pandemic and restrictions
- The methods A and B1 & B2 have been developed and documented (drafts at the moment)
- The validation campaign was due in the middle of the repeated lockdowns (1st and 2nd waves); a contingency plan allowed to carry out a significant set of measurements on diverse standards/artefacts
- The data processing is not mature enough to have a complete picture of the validity of the proposed methods
- Overall, the method A is more mature than B1 & B2; no surprise, it capitalised on the abandoned ISO/TC213/WG10 project on ISO/DTS 15530-2
- The ISO/TC213/WG10 has been regularly informed of the EUCoM progress; a ISO 15530-2 provisional project is up awaiting input from EUCoM
- This seminar could wait no longer to be held, even if the project is not complete; it is a preview of the methods and results; stay connected with the project if you would like to know more in future

Acknowledgement

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