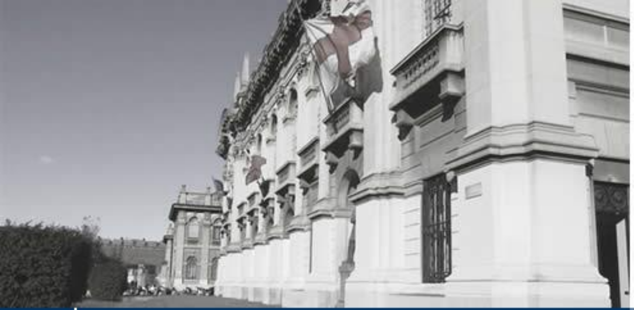


POLITECNICO DI MILANO





CMM: Uncertainty

The problem

How to choose the correct CMM for the measurement of a part?

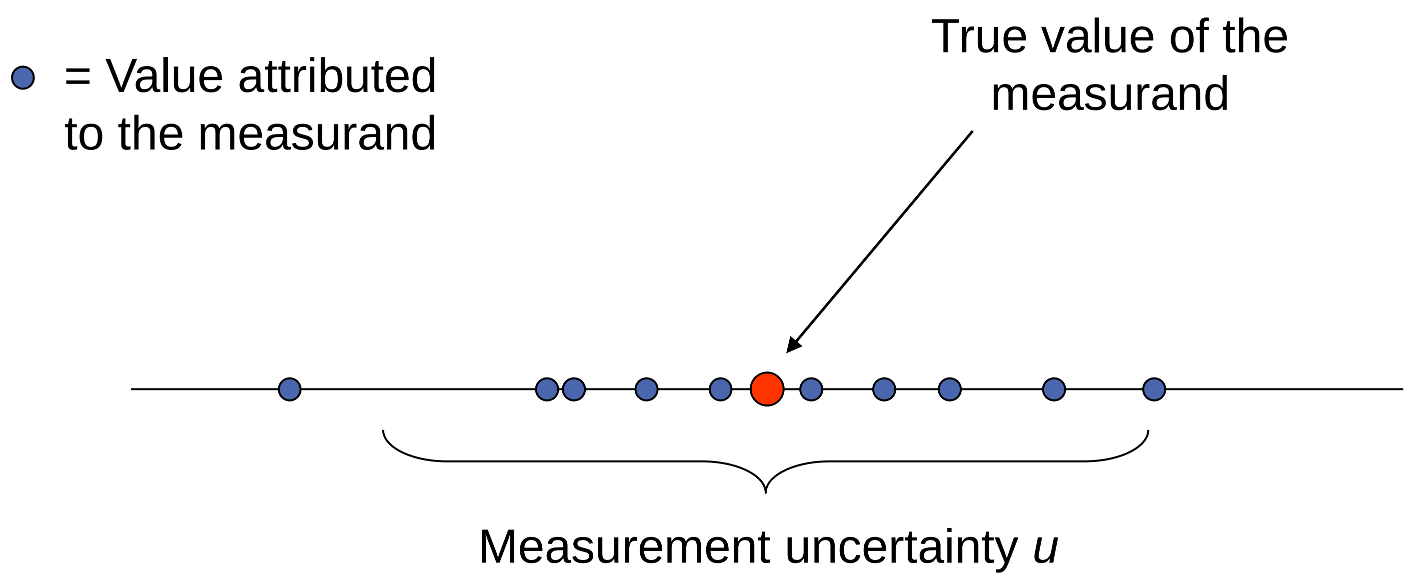
- Is the machine able to perform the measurement? → CAIP
- Is the measurement result accurate enough? → …?

Measurement uncertainty

Definition of measurement uncertainty (UNI CEI ENV 13005):

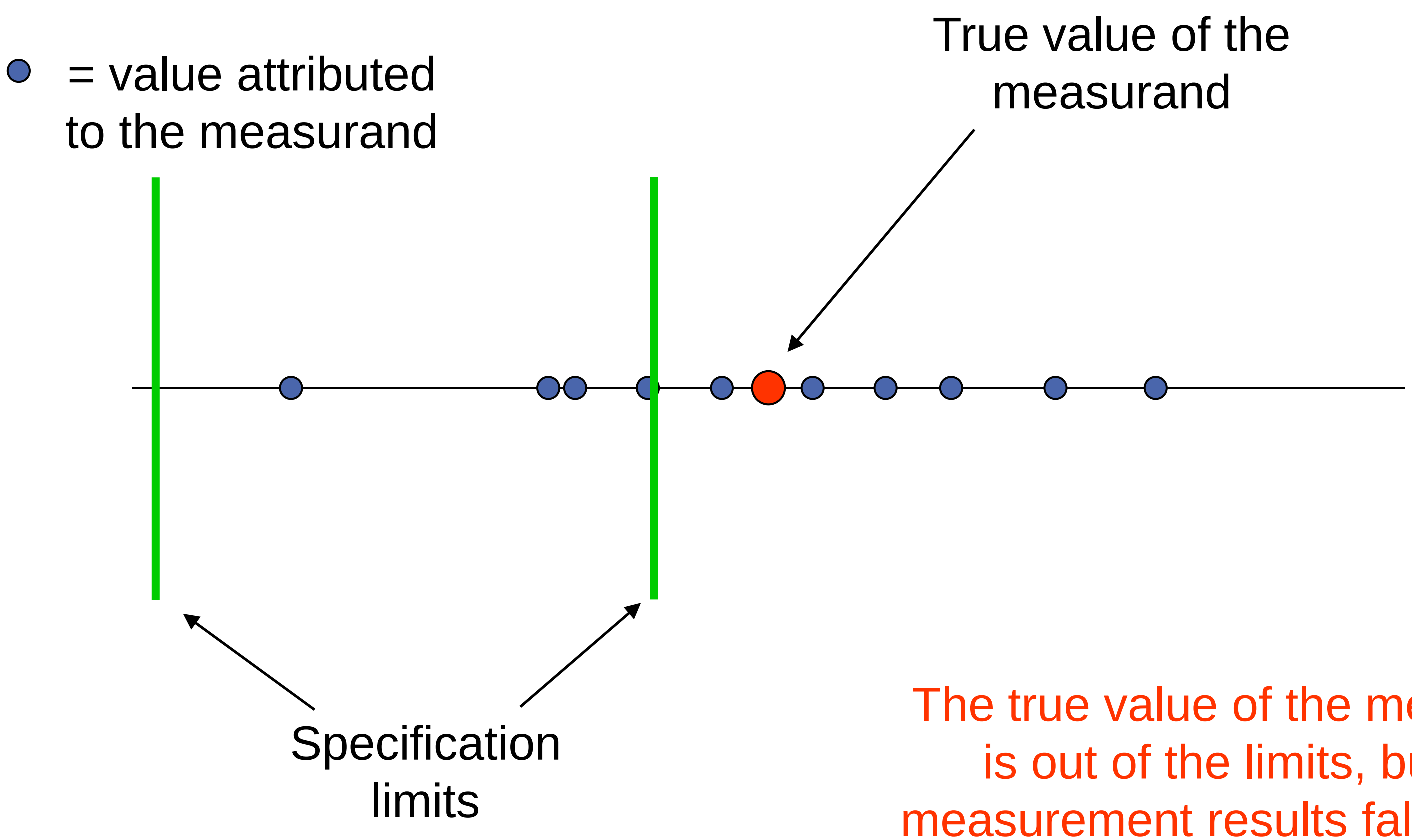
“**non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used”**

It’s a measurement of the quality of the measurements!



Impact of the uncertainty

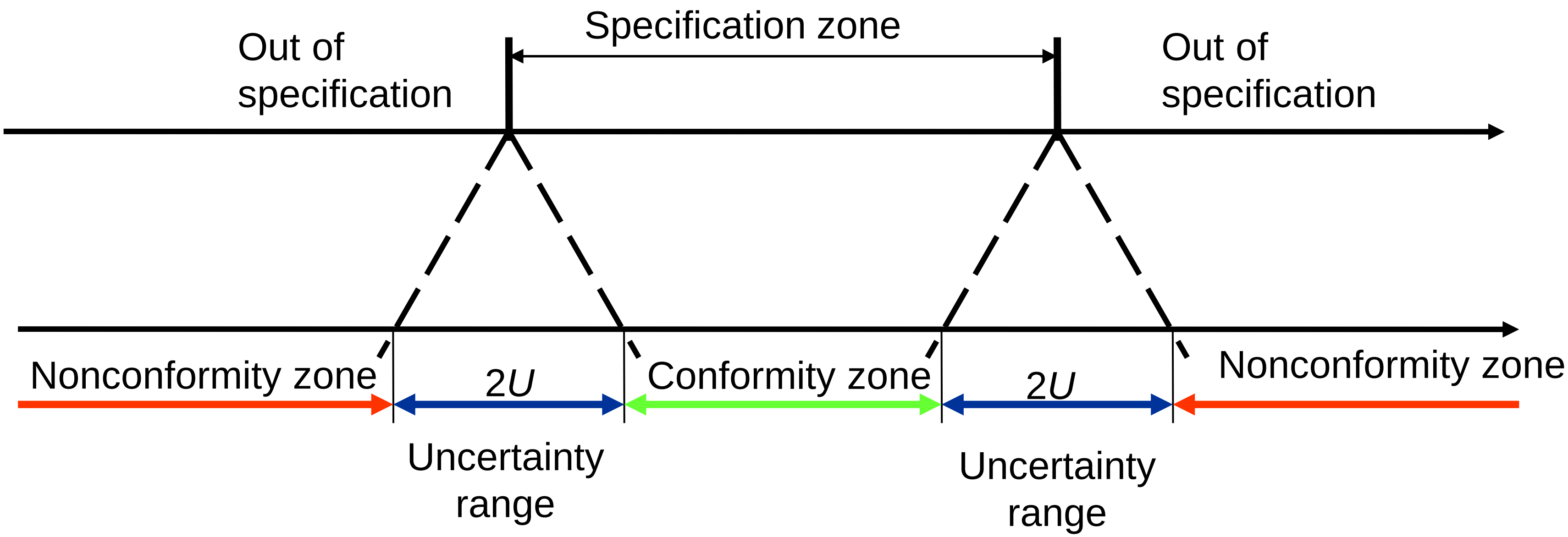
Problem: let’s suppose there exist any specification limit



The true value of the measurand is out of the limits, but few measurement results fall between them. How to manage this situation?

Impact of the uncertainty

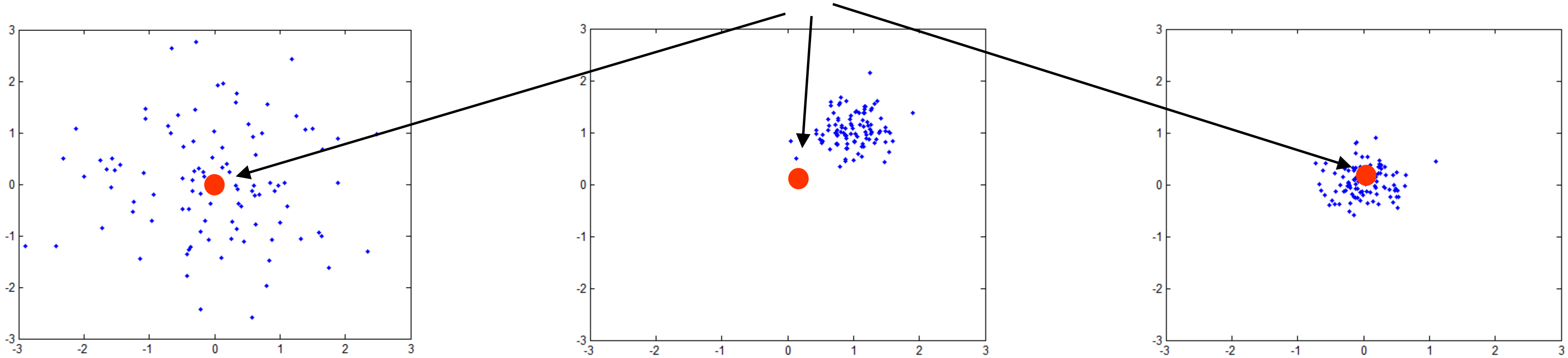
ISO 14253-1 Standard



- A measurement result either in the conformity or non conformity zone always denotes a conformity o a nonconformity to some specification statement.
- A measurement result in the uncertainty range denotes a nonconformity if the aim is to prove conformity, or a conformity if the aim is to prove nonconformity.

Systematic and Random errors

True value of the measurand



“True” “Precise” “Accurate”

General model of a measurement:

$$y = x + \varepsilon$$

$$\varepsilon \sim D(\mu, \sigma)$$

$$y \sim D(\mu + x, \sigma)$$

True value of the measurand

Measurement error

Measurement result

Bias or systematic error

Random Error

Measurement uncertainty

$$y = x + \varepsilon$$
$$\varepsilon \sim D(\mu, \sigma)$$
$$y \sim D(\mu + x, \sigma)$$

The bias is corrected: calibration

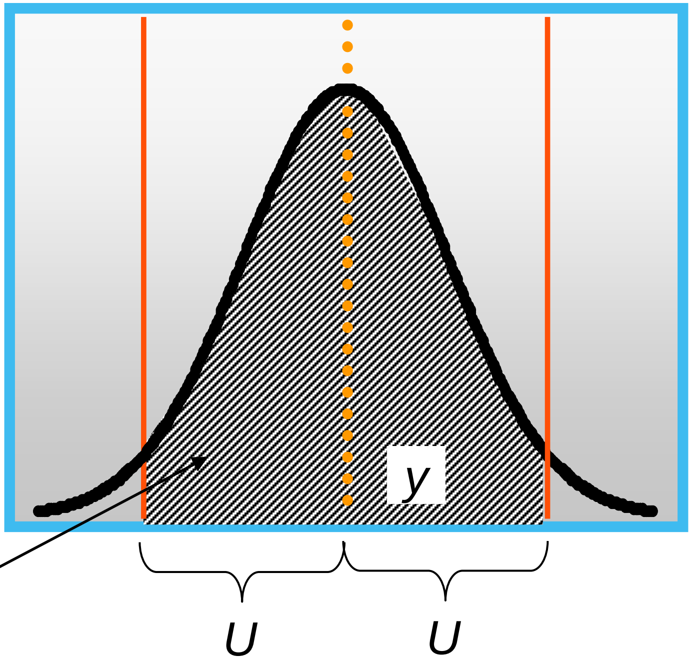
$$y' = x - \mu + \varepsilon$$
$$\varepsilon \sim D(\mu, \sigma)$$
$$y' \sim D(x, \sigma)$$

In general, the random error cannot be corrected: it generates the measurement uncertainty (cfr ISO GUIDE 98-3 “GUM” and ISO GUIDE 99 “VIM”)

$u = \sigma$ “standard uncertainty”

$$U = k * u = k * \sigma$$

“expanded uncertainty”



“Confidence level”

Uncertainty estimation

Measurement uncertainty must be estimated:

- Category A estimation: based on the variance of multiple observations

$$y = \frac{1}{n}\sum_{j=1}^{n} y_j \qquad u^2(y) = \frac{1}{n(n-1)}\sum_{j=1}^{n}\left(y_j - y\right)^2$$

- Category B estimation: based on other information
  - Former measurements
  - Operator experience
  - Instrument manufacturer information
  - Instrument calibration certificates
  - Reference uncertainty from manuals
  - Simulation

Combined uncertainty

Let’s suppose the measurement result comes from the combination of several different measurement results:

$$y = f\left(y_1, y_2, \ldots, y_n\right) \qquad Y = f\left(Y_1, Y_2, \ldots, Y_n\right)$$

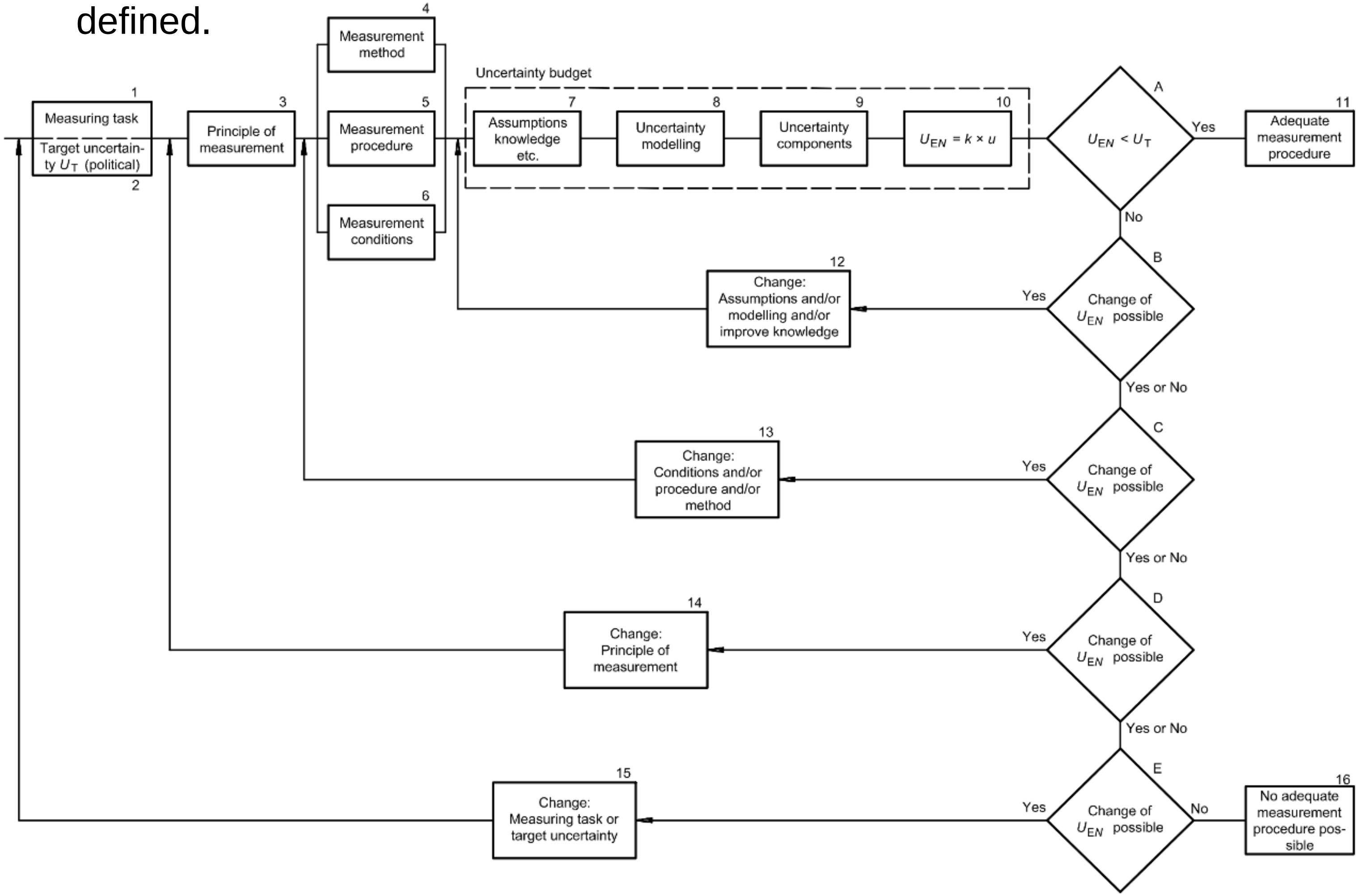
If the *n* measurements are independent, then

$$u_c^2\left(y\right) = \sum_{i=1}^{n}\left[\left.\frac{\partial f}{\partial Y_i}\right|_{y_i} u\left(y_i\right)\right]^2$$

Measurement uncertainty - GPS

In the field of GPS, the reference standard is the ISO/TS 14253-2

- PUMA (Procedure for Uncertainty MAnagement) method: the measurement uncertainty is cyclically estimated, until an adequate measurement procedure is defined.



Measurement uncertainty - CMM

However, the PUMA method does not describe how to estimate the uncertainty, but just how to manage it. The problem of the evaluation of the uncertainty and the performance of a CMM has been divided in two series of standards:

ISO 10360

“Acceptance and reverification tests for coordinate measuring machines”

They define the performance of a CMM through a series of tests and related performance indicators (MPE).

ISO 15530

“Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement”

Simplified methods for the evaluation of the uncertainty of CMMs

Performance indices ISO 10360-4 and -5

$P_{\mathrm{FTU,MPE}}$ maximum permissible single-stylus form error

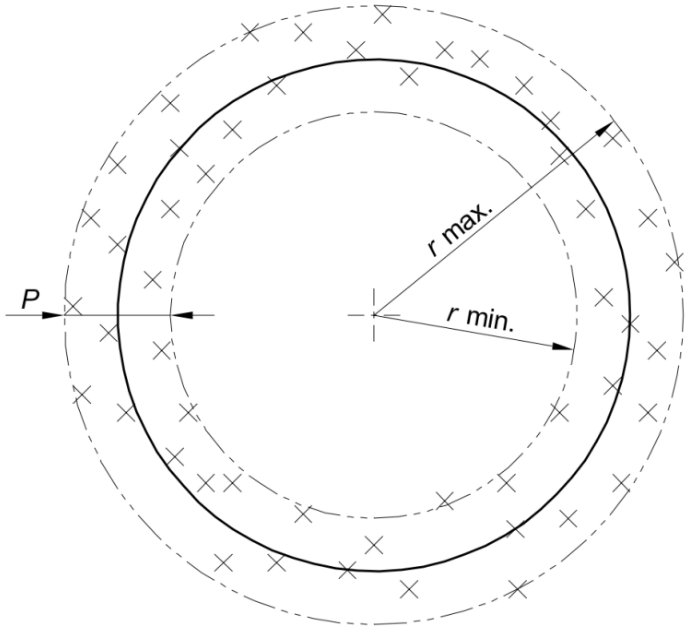
– extreme value of the single-stylus form error, PFTU, permitted by specifications, regulations, etc. for a CMM.

$P_{\mathrm{FT}j\mathrm{,MPE}}$ maximum permissible multi-stylus form error

– extreme value of the multi-stylus form error, PFTU, permitted by specifications, regulations, etc. for a CMM.

MPE_{Tij} maximum permissible scanning probing error

– extreme value of the multi-stylus form error, PFTU, permitted by specifications, regulations, etc. for a CMM.



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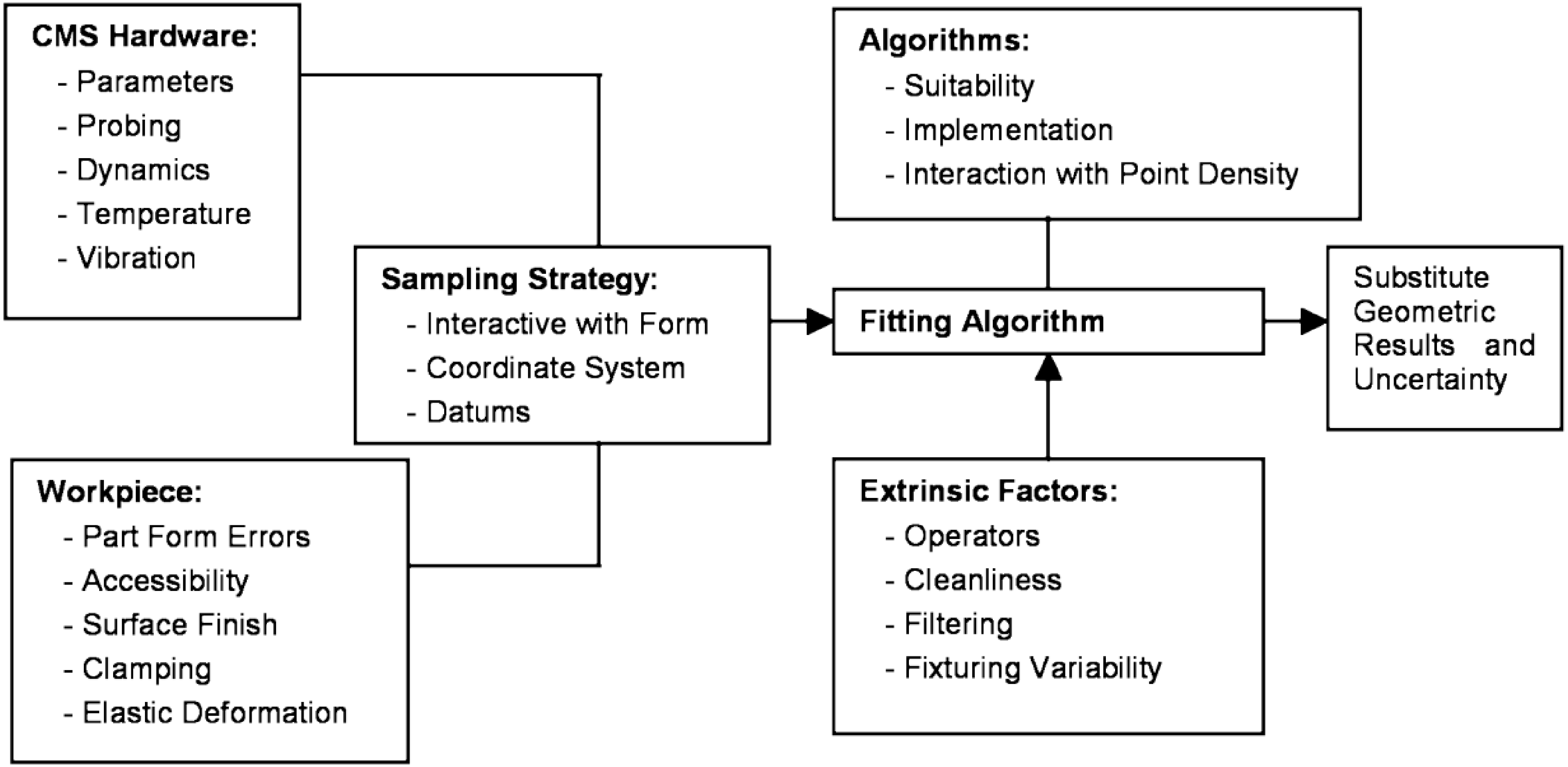
Simplified methods for the evaluation of the uncertainty of CMMs

Uncertainty sources for a CMM

Task specific uncertainty



Measurement uncertainty – CMM – VCMM

The limits of the proposed procedure lead to the search for a procedure which is

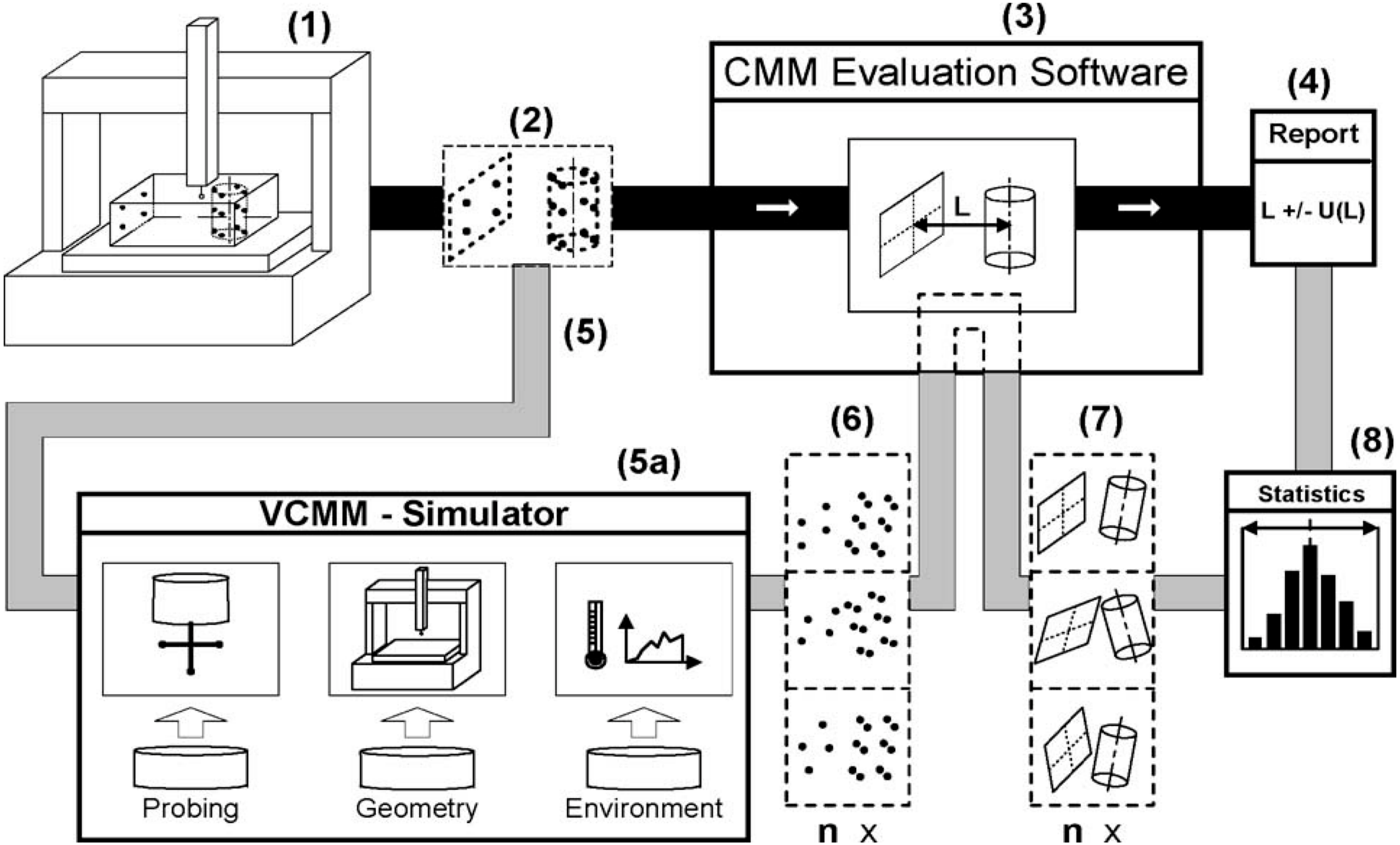
- fast
- easy to apply
- flexible

I.e. able to evaluate the task specific measurement uncertainty.

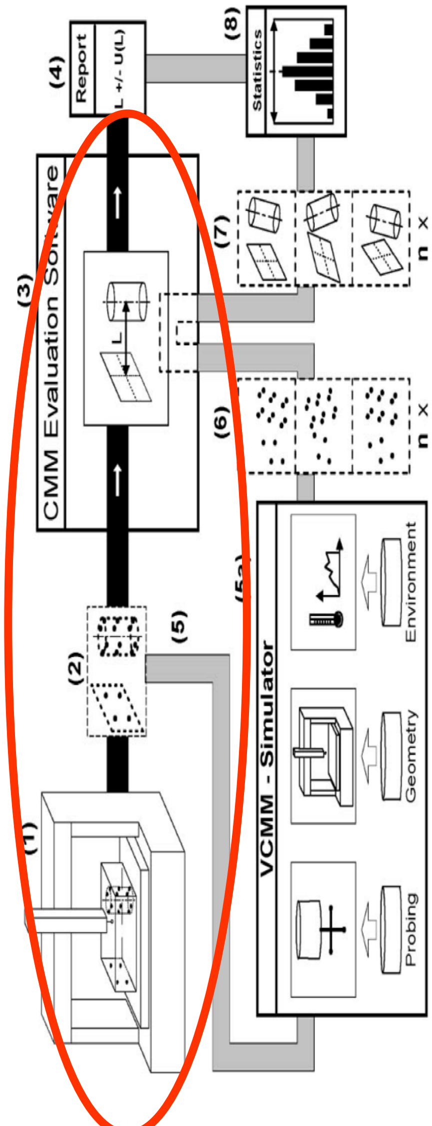
A methodology characterized by these features is the one based on a "Virtual CMM" (VCMM)

"The virtual coordinate measuring machine (VCMM) approach estimates an uncertainty statement for a particular measurement task on a particular CMM according to **Monte Carlo simulation** results" (Wilhelm, R. G.; Hocken, R. & Schwenke, H. **Task Specific Uncertainty in Coordinate Measurement**. *CIRP Ann-Manuf. Technol.*, Elsevier, 2001, 50, 553-563

VCMM – scheme of the procedure



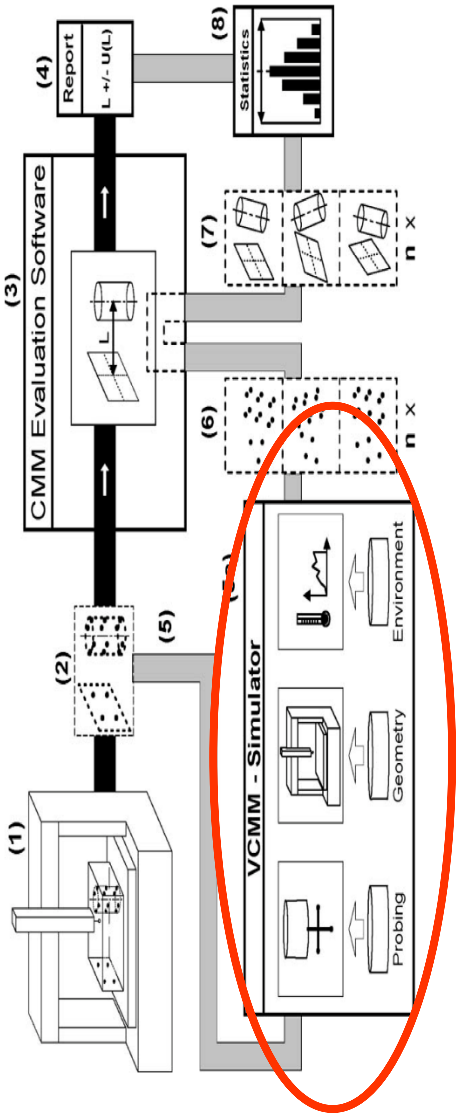
VCMM - operation



The VCMM needs some input. These can e.g. include (ISO/TS 15530-4):

- The CMM performance according to the 10360 standard
- The measurement of one or more calibrated artifacts in some specified position within the measuring volume of the CMM
- A “Gauge R&R” study
- Some expert evaluation

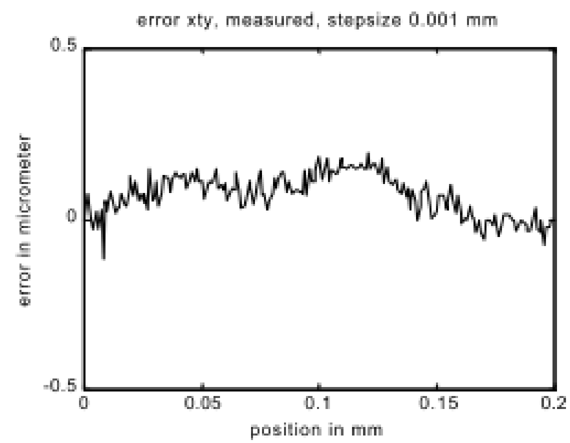
VCMM - operation



The core of a VCMM is the measurement simulator.

Simulations can be operate in several different ways:

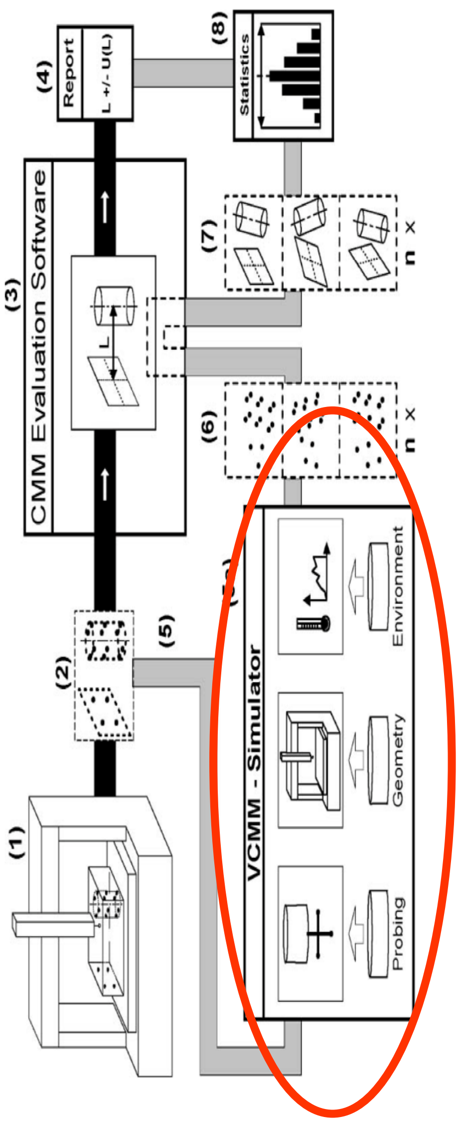
- By applying real measurement errors on single points to the actual measurement results



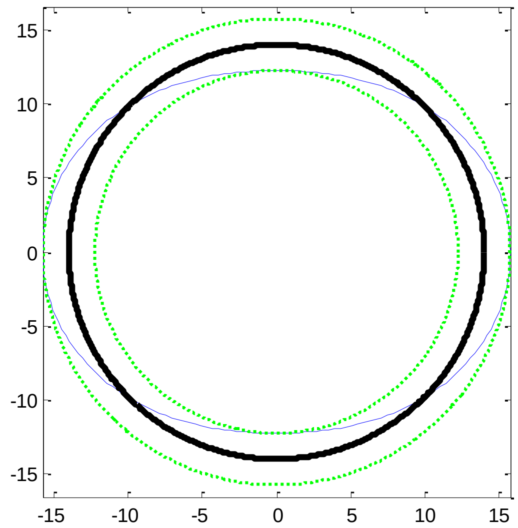
- Based on some spatial statistical model of the measurement error at a specific point

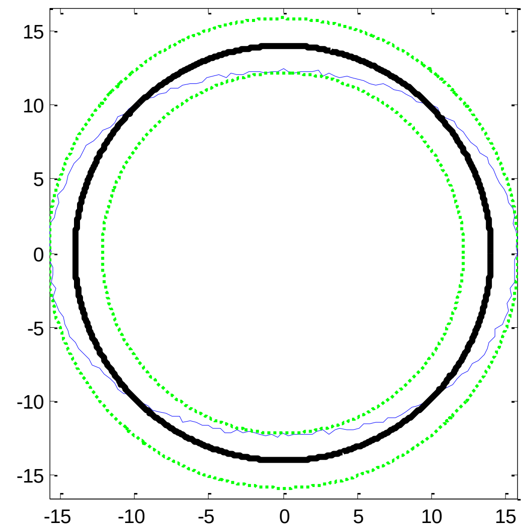
$$\mathbf{e} = N(\mathbf{0}, \mathbf{\Sigma}) \qquad \sigma_{i,j} = \sigma_{i,j}(x_i, y_i, z_i, x_j, y_j, z_j)$$

VCMM - operation



A series of «nominal» profile are simulated for which the expected measurement result is known. The nominal profiles are perturbed according the VCMM model, and a perturbed measurement result is obtained.



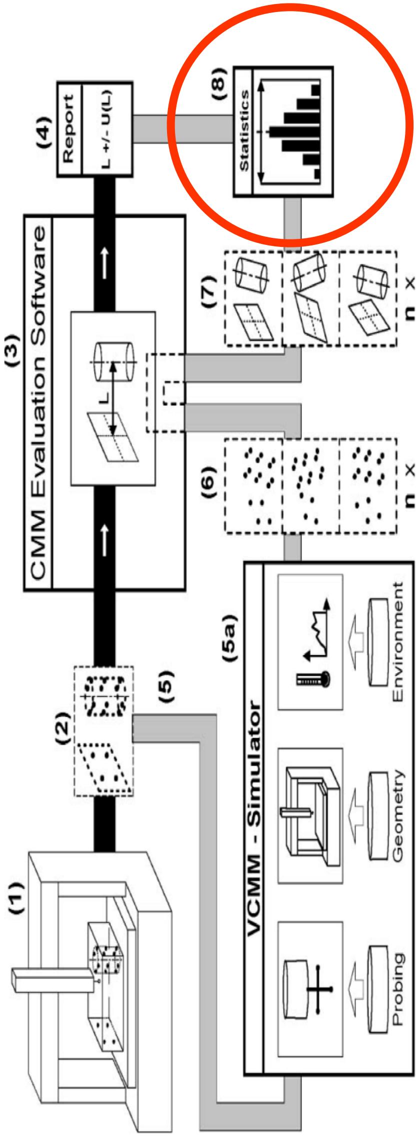


Nominal profile

Perturbed profile

Simulated measurement error

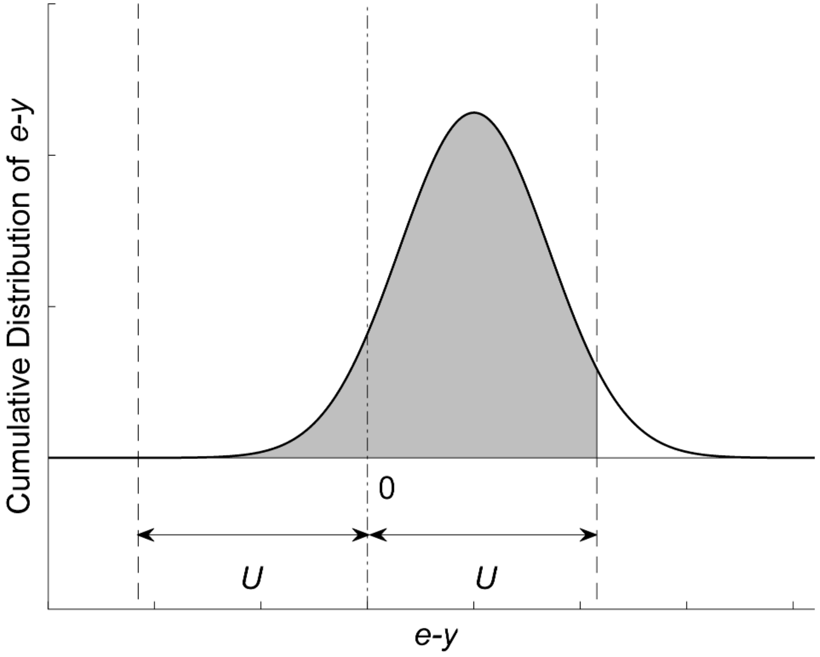
VCMM - operation



The uncertainty can be extrapolated in several ways. For instance* one can calculate U so that

$$G(U) - G(-U) = 0.95$$

Where G is the empirical cumulative function of the measurement errors.



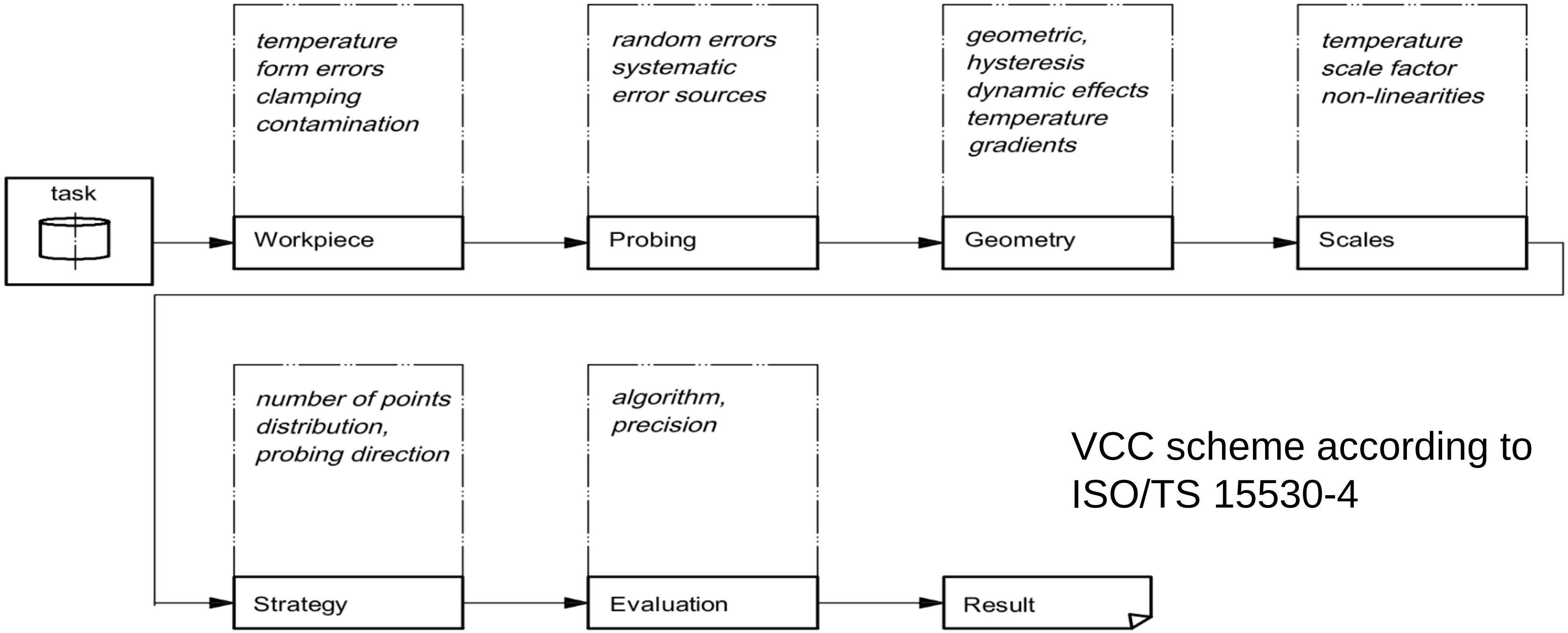
*https://doi.org/10.1016/S0007-8506(07)62973-4

Measurement uncertainty – ISO/TS 15530-4

VCMMs are regulated by the ISO/TS 15530-4 standard: “Evaluating task-specific measurement uncertainty using simulation”

The standard requires:

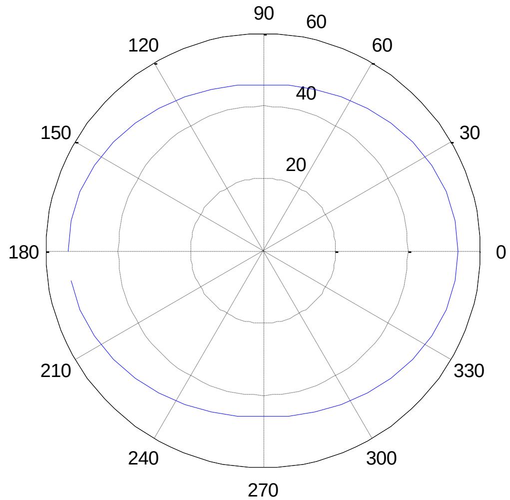
- The fundamental requirements which define the VCMM
- The fundamental methods for the VCMM validation



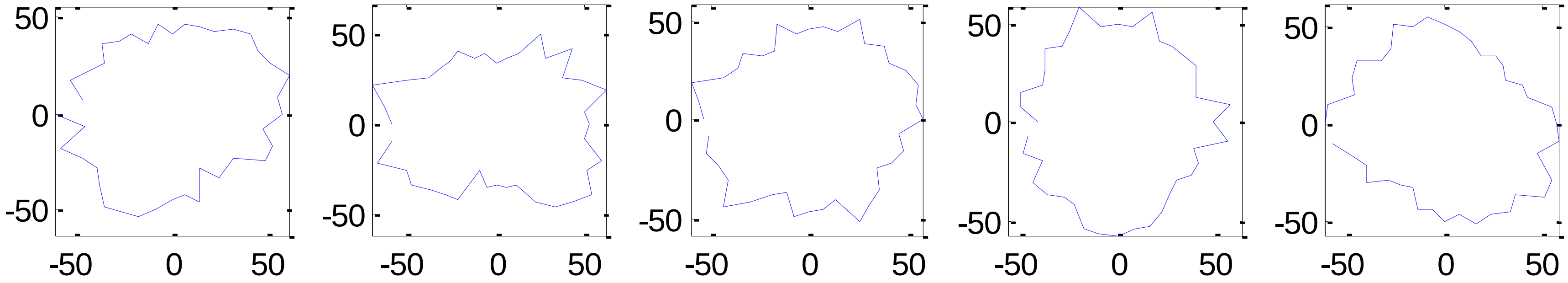
VCC scheme according to ISO/TS 15530-4

VCMM - Example

Let's suppose we aim at estimating the measurement uncertainty for the verification of roundness on a calibrated plug gauge measured on 40 points.



Nominal profile
(roundness deviation 0.32 μm)



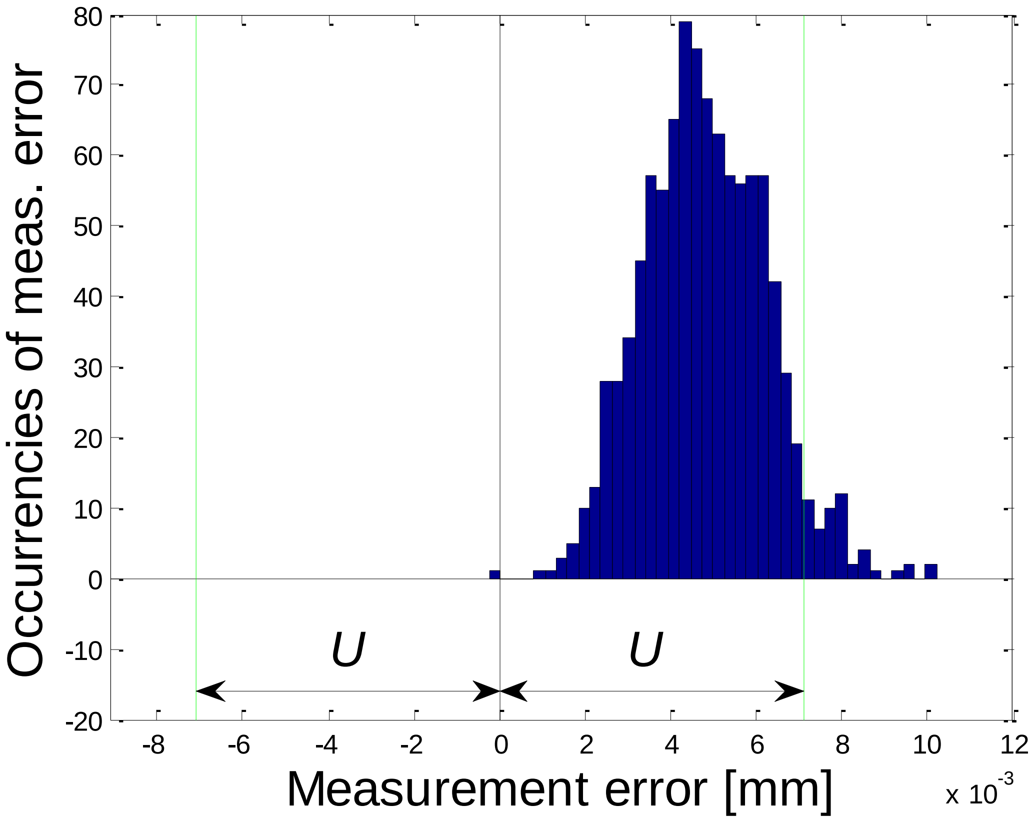
… 1000 replicas ➔ 1000 simulated measurement errors

VCMM - Example

Let's put everything on an histogram...

And let's extract the uncertainty.

$$G(U) - G(-U) = p$$



VCMM - Example

Let’s apply the ISO/TS 15530-4 to validate the result.

- Let’s take a calibrated plug gauge (calibrated roundness deviation 0.32±0.15 μm).
- Let’s perform 100 measurements.
- Let’s estimate the uncertainty: U=1.0 μm

Results are compared by means of the formula:

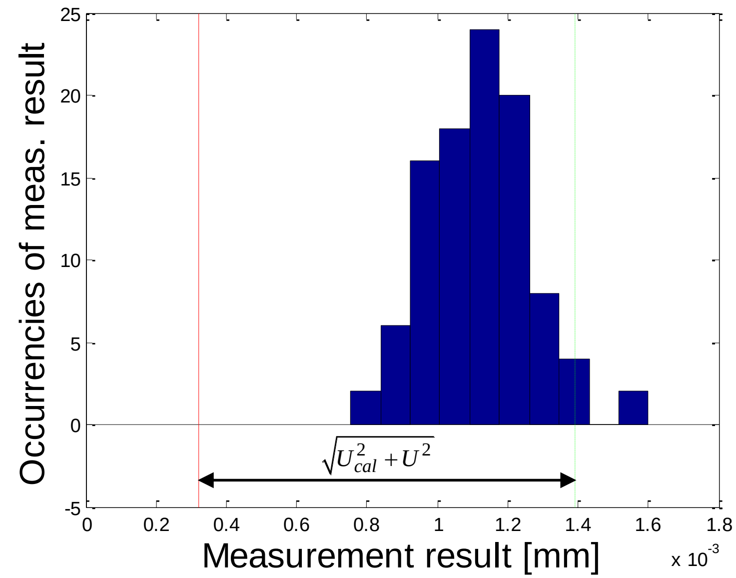
$$|y_{cal} - y| \leq \sqrt{U_{cal}^2 + U^2}$$

Reference value

Measured value

Calibration uncertainty

VCMM uncertainty

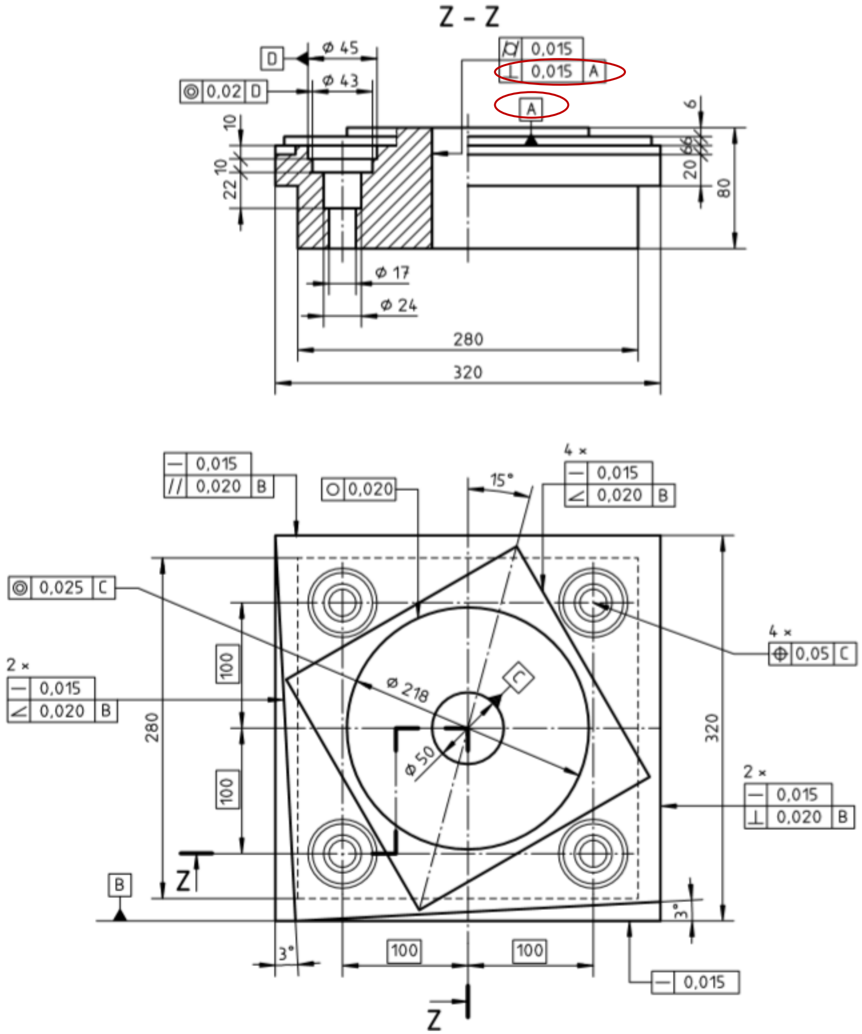


Which is satisfied 97 times,

coherent with what was expected (95).

What to do now…

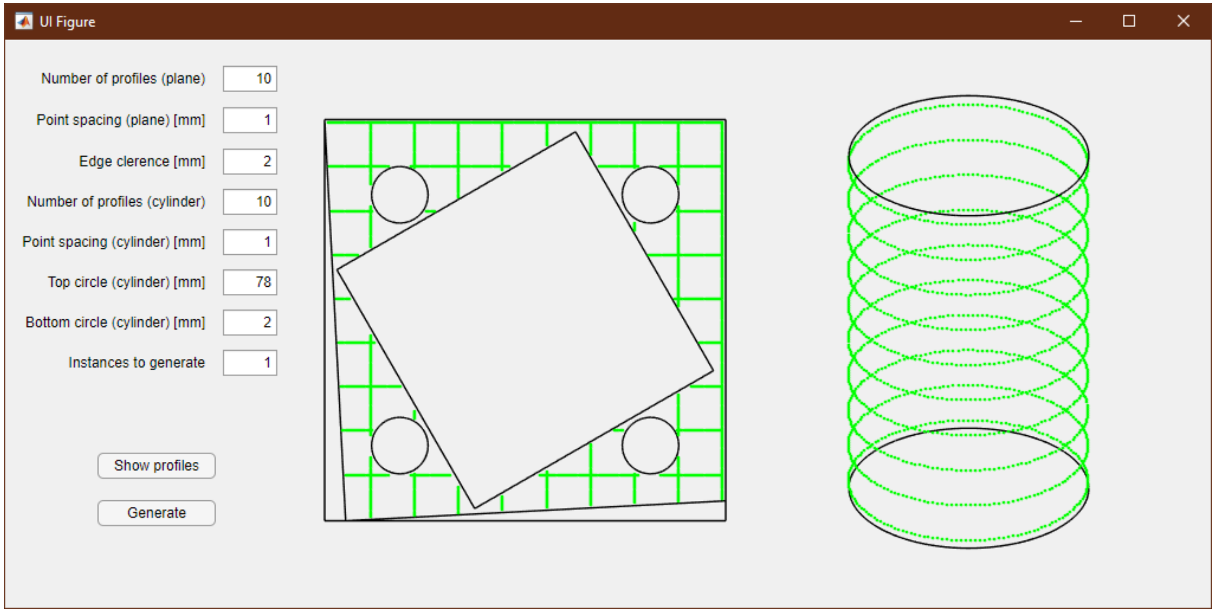
Focus on the perpendicularity tolerance of the center hole



What to do now…

Step 1: generate reference values and cloud of points for the central hole and datum A

- Define the sampling strategy
  - The strategy must be coherent with the probe configuration and part fixturing!
- Choose how many instances to generate
- Use the provided matlab software



What to do now…

Step 3: Perturb the generated cloud of points.

- Consider the maximum probing error as defined in the brochure as reference for the generation probing error. Justify why you generated the error this way.

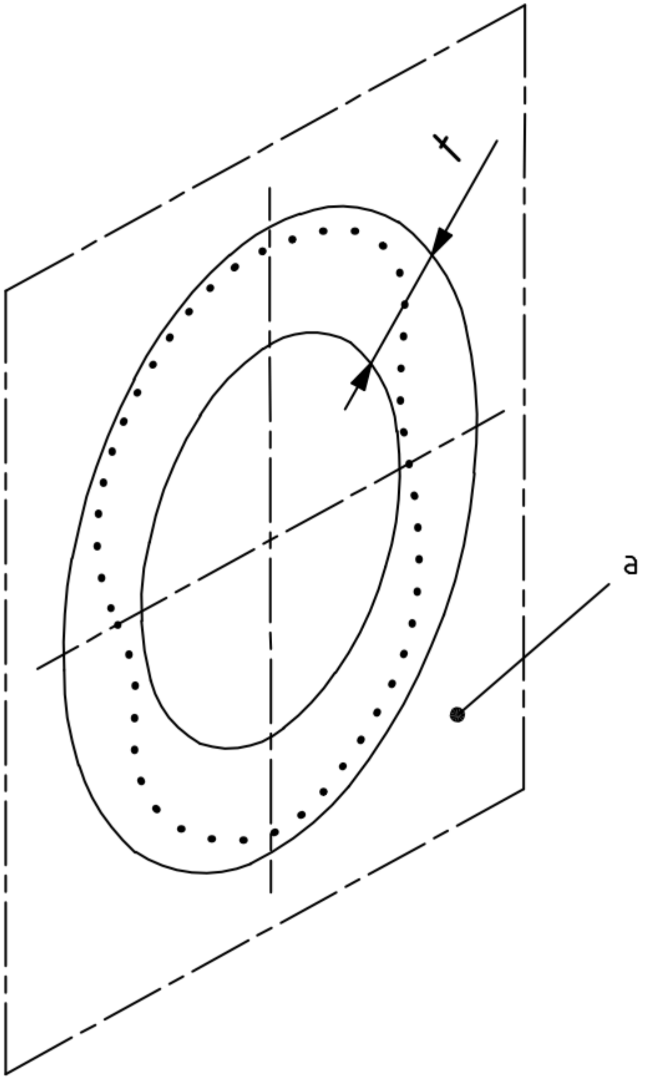
Step 4: fit the datum and the toleranced feature and calculate the squareness deviation.

Step 5: from the calculated squareness deviations estimate the uncertainty

Step 6: evaluate whether the uncertainty is adequate or not.

Es. 1: roundness

- Generate a round Ø10 mm profile characterized by a 0.02 mm global roundness deviation in np points.
- Simulate n profiles in which a perturbation is added, the perturbation being generated from a $N(0{,}0.001^2)$ gaussian distribution.
- Calculate the roundness deviation (use minimum zone fitting) per each profile.



Es. 2: roundness - correlation

- Generate a round Ø10 mm profile characterized by a 0.02 mm global roundness deviation in np points.
- Generate a perturbation being as*

$$p_i = \sum_{j=1}^{np} \frac{\rho_{i,j}}{n_i} p_j + \varepsilon_i$$

$$(\mathbf{I} - \rho\mathbf{N})\mathbf{p} = \boldsymbol{\varepsilon}$$

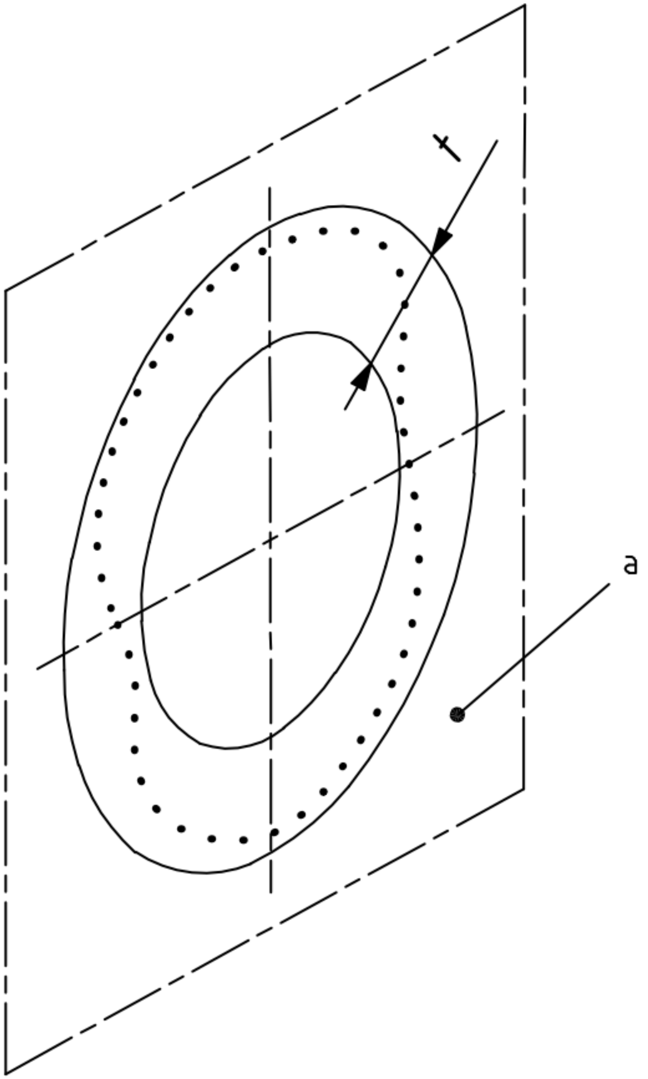
$$\rho_{i,j} = \begin{cases} \rho, points\ i\ and\ j\ are\ adjacent \\ 0, else \end{cases}$$

n_i is the number of points adjacent to point i

$$\rho = 0.9$$

$$\varepsilon_i \sim N(0{,}0.001^2\ )$$

- Rescale the perturbation so that its variance equals the original variance of the generated ε_i. Apply it to the nominal profile to generate the perturbed profile.
- Calculate the roundness deviation (use minimum zone fitting) per each profile.



*Spatial autocorrelation model