Measurement uncertainty evaluation with a posteriori method

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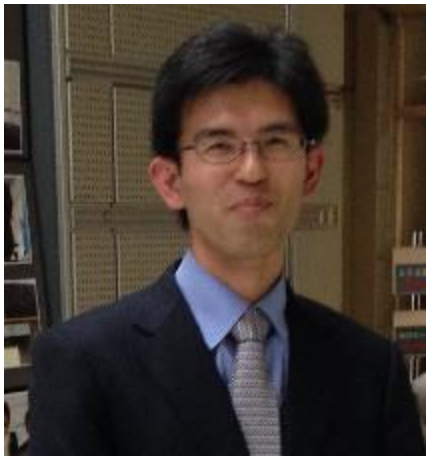
Speaker



Osamu Sato, Ph.D.

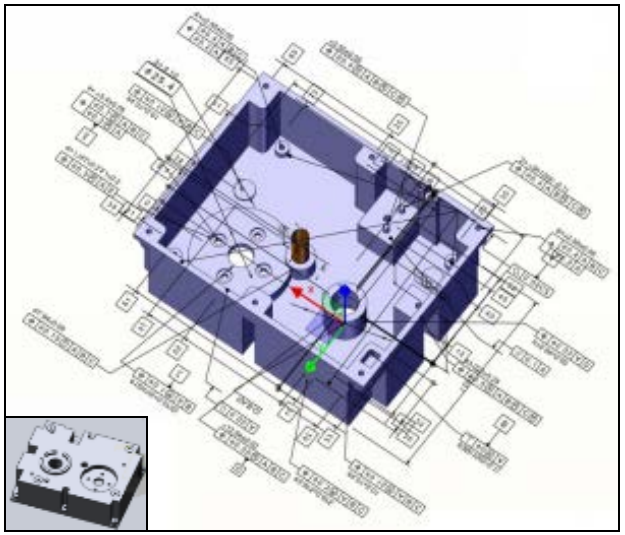
- Calibration authority in NMIJ/AIST
  - Geometrical features measurement using CMMs
- Senior researcher in dimensional standard section, REIM, NMIJ/AIST
- ISO/TC 213/WG 4, WG 10 expert (JP)
- Role in EUCoM Project
  - Development of uncertainty evaluation procedure and measurement protocol for calibration of:
    1. size/angle,
    2. single features, datum related features, and
    3. profile features on prismatic and freeform artefact.

Overview

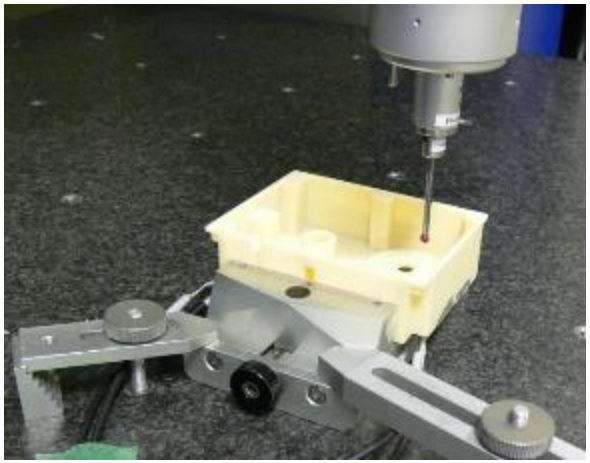
- Demand: evaluate measurement uncertainty using CMM
- Situation: less information for uncertainty estimation
  - CMM's property
  - Uncertainty contributors
  - Detail measurement data
- Situation: less resources for uncertainty estimation
  - Special equipment
  - Software
  - Operator's effort
- Solution proposal: a posteriori method w/o special materials
  - Multiple measurement
  - ANOVA

Dimensional measurement using CMMs

- Suitable for complex GPS validation
- Hard to estimate measurement uncertainty
  - Several number of uncertainty contributors



Designed geometrical features



Product verification using a CMM

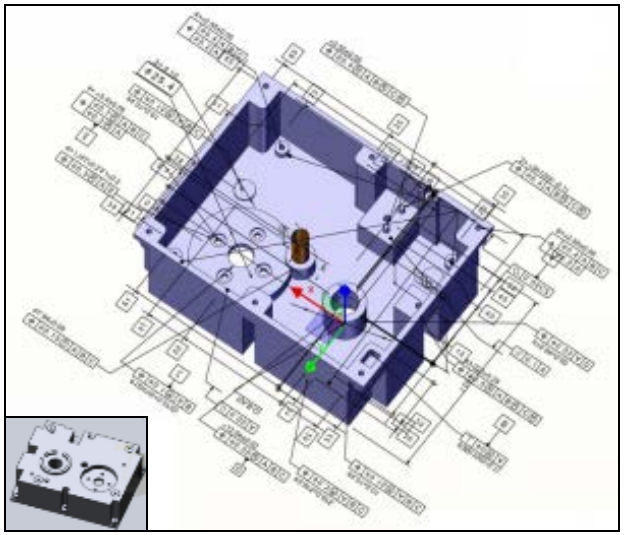
Uncertainty evaluation application

1. Calibration of the workpiece
   - Calibration certificate
     - Calibration value
     - Calibration uncertainty
     - Traceability

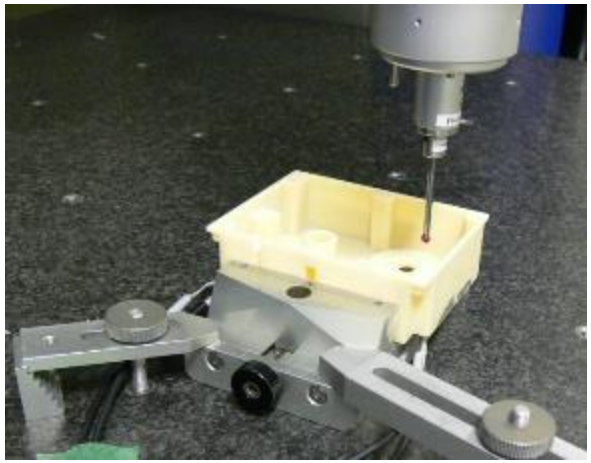
2. Inspection of the workpiece
   - Conformity/non conformity
     - Measurement value
     - Measurement uncertainty
     - Traceability

Dimensional measurement using CMMs

- Development of an uncertainty estimation method for ordinary measurement operation using CMM in factory floor.
  - Equipment, software function, etc..



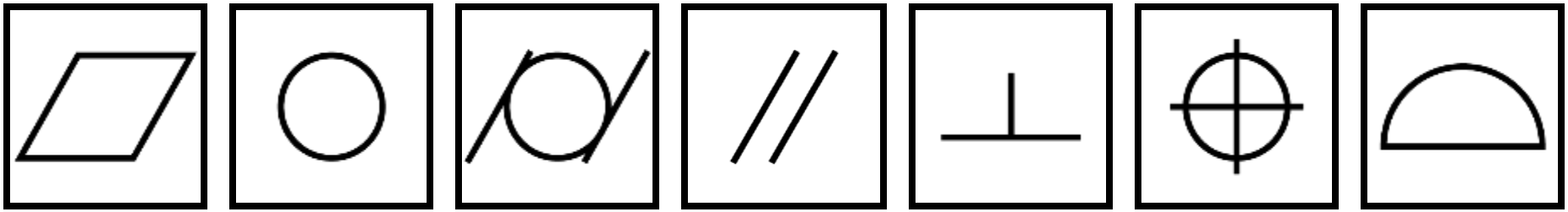
Designed geometrical features



Product verification using a CMM

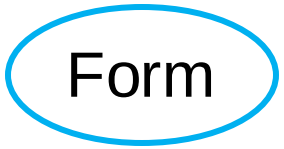
Target measurands

- It's possible to evaluate many kinds of geometries of artefacts using CMMs.
  - Parameters derived from points coordinates.
- The developing method focuses on limited geometries.
  - Because actual/practical products are designed with the combination of several geometries.
  - Parameters defined related to geometric tolerances, e.g.,



Target parameters in the development

- Length and angle (size/distance)
- Relative position/location/orientation
- Single features
  - e.g. straightness, flatness, roundness
- Related features
  - e.g. parallelism, squareness
- Deviation from associated/designed features
  - e.g. profile



Uncertainty estimation method

- Published methods
  - Uncertainty budget (GUM)
  - Substitution method
    - ISO 15530-3
  - Monte Carlo simulation
    - ISO/TS 15530-4

- Developing methods
  - A posteriori method
    - former DTS 15530-2
  - A priori knowledge

Example of GUM's manner

Uncertainty budget

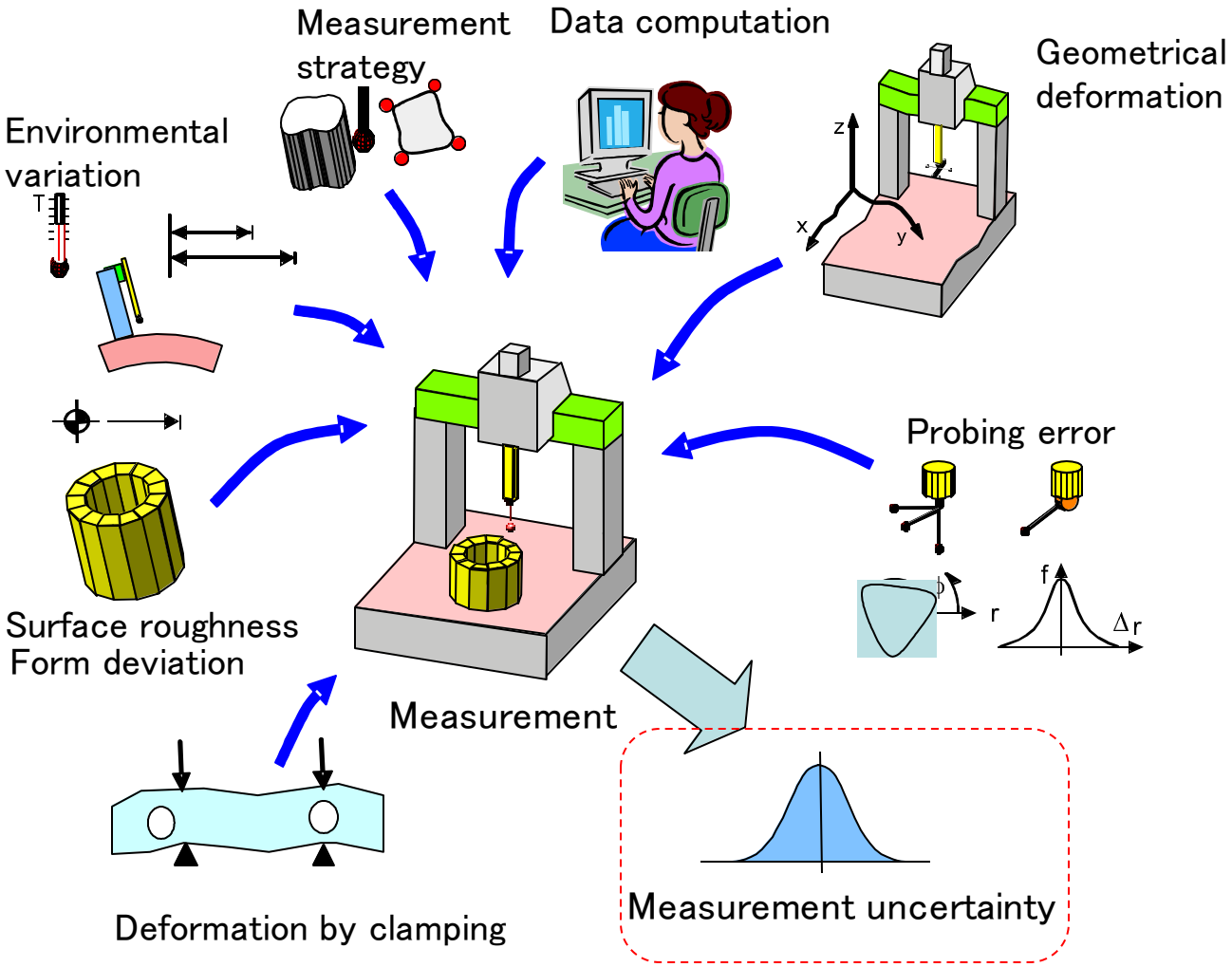
Length independent		213	nm			
No	Item	Size	Unit	Type	u	
1	Probing error (WS measurement)	100	nm	B		
2	Probing error (RS measurement)	100	nm	B		
3	Repeatability	230	nm	A		
4	Reproduceability	234	nm	A		
5	Form error	100	nm	B		
6	Error propagation	40	nm	B		
7	Geometrical error of CMM	150	nm	B	87	nm
8	RS calibration value (uni-directional)	134	nm	B	134	nm

Length dependent		252	nm/m			
No.	Item	Size	Unit	Type	u	Unit
9	Abbe error	23	urad/m	B	7	n
10	Scale compensation	109	nm/m	B	109	nm
11	CTE of WS	5.E-07	/K	B	2	nm
12	CTE of RS	5.E-07	/K	B	0	
13	Temperature measurement (WS)	5	mK	B	0	n
14	Temperature measurement (RS)	7	mK	A	0	n
15	Thermal drift (WS measurement)	5	mK	B	0	n
16	Thermal drift (RS measurement)	24	mK	A	0	nm
17	Cosin error	0.1	mm/mm	B	0	nm
18	RS calibration value (uni-directional)	227	nm	B	227	nm

Centre-to-centre distance calibration

Estimation for simple workpiece is ENOUGH complex

Uncertainty contributors in CMM measurement task



Uncertainty contributors

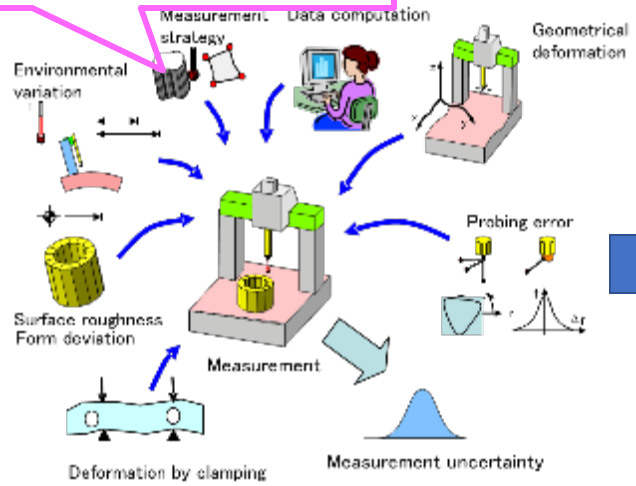
- Environment for meas.
- Reference element of meas. equipment
- Meas. equipment itself
- Meas. setup
- Software/calculation method
- Meas. operator
- Workpiece property
- Definition of the measurand
- Meas. procedure
- Physical constants

Measurement in factory floor

Uncertainty modules

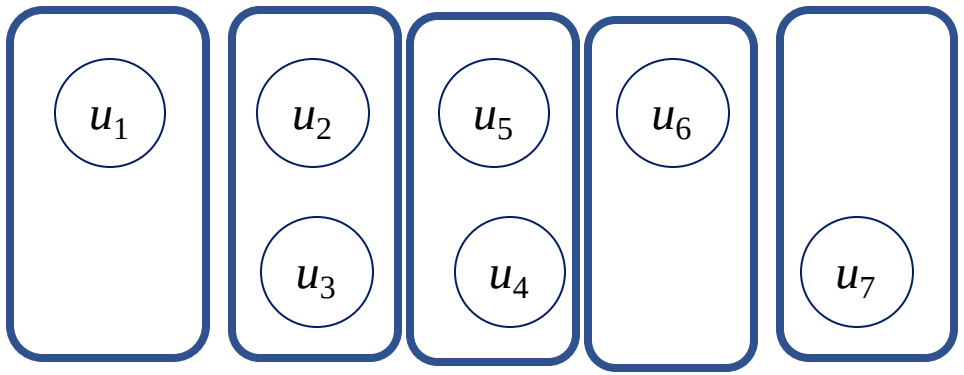
- Previous development (DTS 15530-2)
  - u_{rep}, u_{geo}, E_L, u_{corr}, E_D, u_D, u_{temp}
  - and other modules to be considered

Hard to evaluate
Complex task



Uncertainty contributors

Easy to evaluate
Simple task



Uncertainty modules

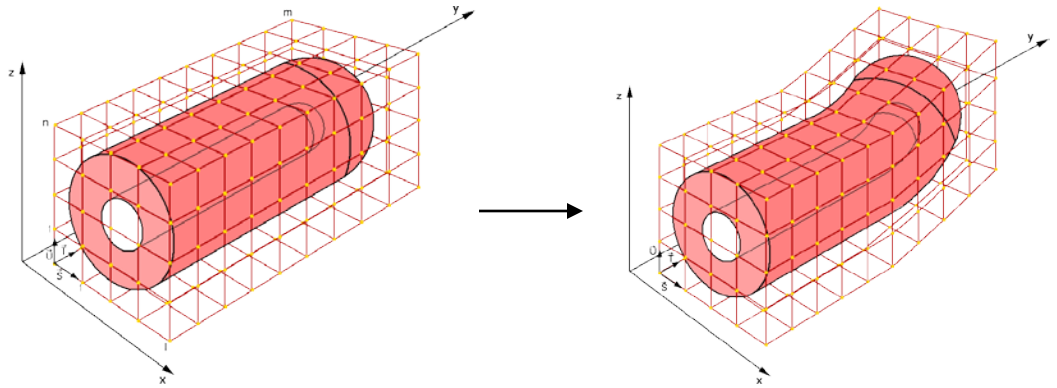
Strategy of uncertainty assessment

- Modularize the dominant measurement uncertainty
  - Known/unknown systematic error
  - Random error

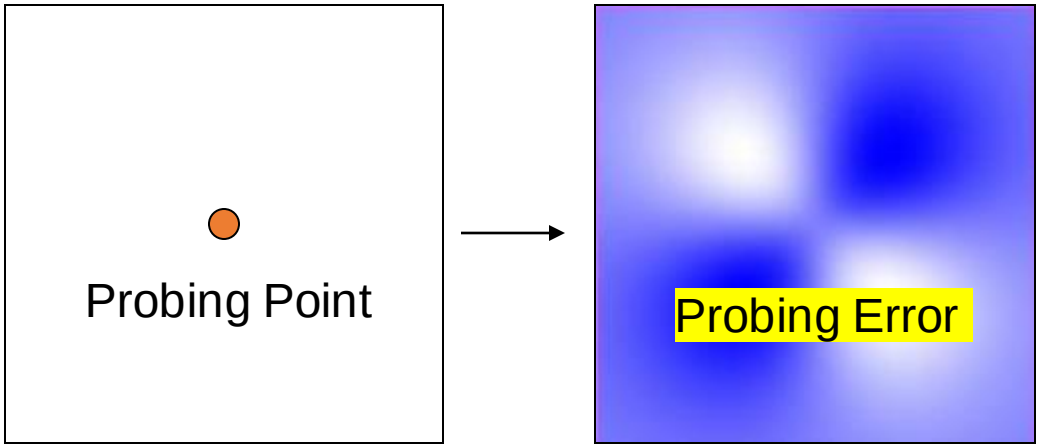
- Practical experimental design
  - Workpiece measurement in several varied conditions
  - Workpiece measurement with several repetitions
  - Analysis of variance

Dominant errors in coordinate measurement domain

- Global error
  - Deformation of the coordinate system

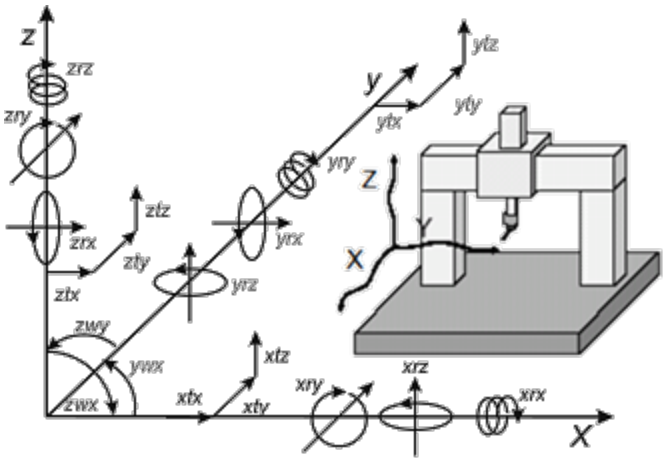


- Local error
  - Bias and fluctuation of the sensing

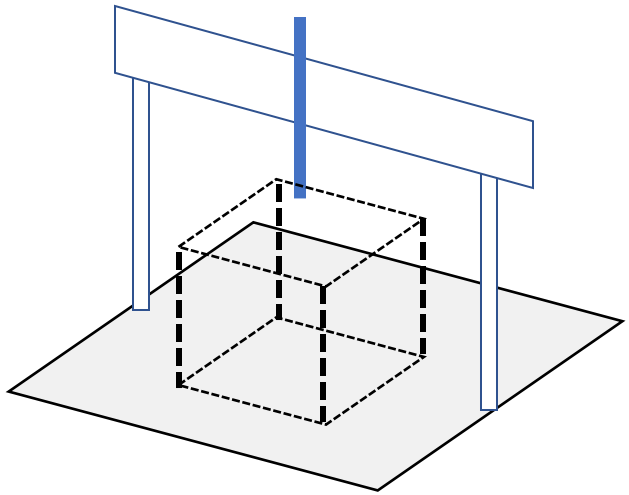


Assessment on the coordinate system deformation

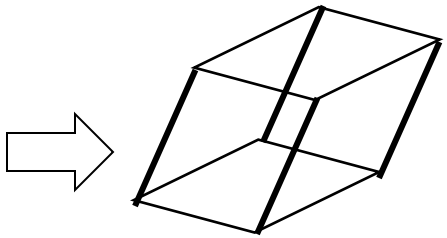
- Background
  - Region of interest (ROI) in CMM's measurement volume is a parallel pipe, which is a deformed cubic ROI by several factors.



Geometrical errors in CMM's frame

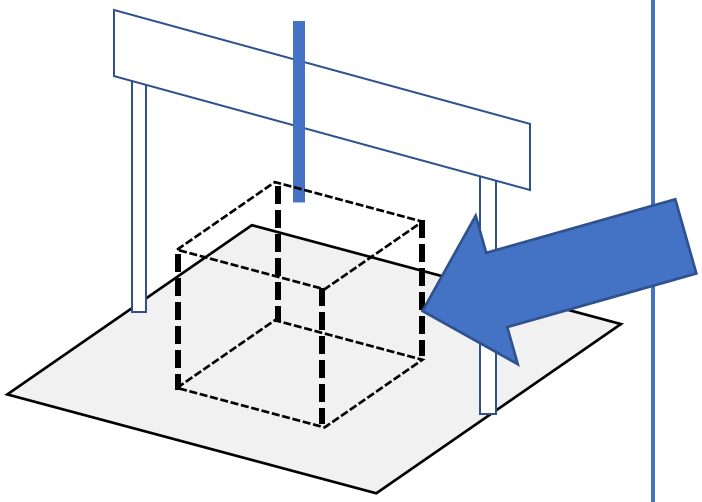


Cubic ROI

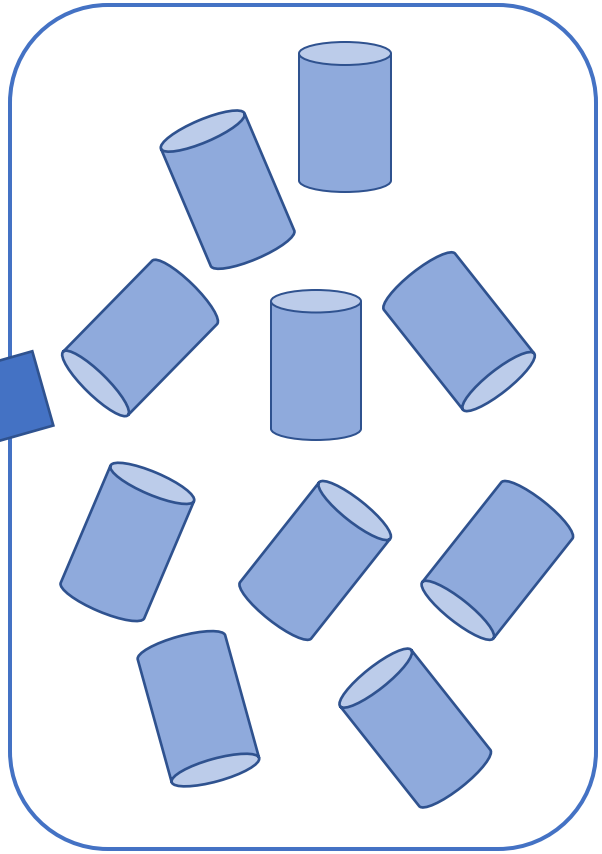


Deformed ROI

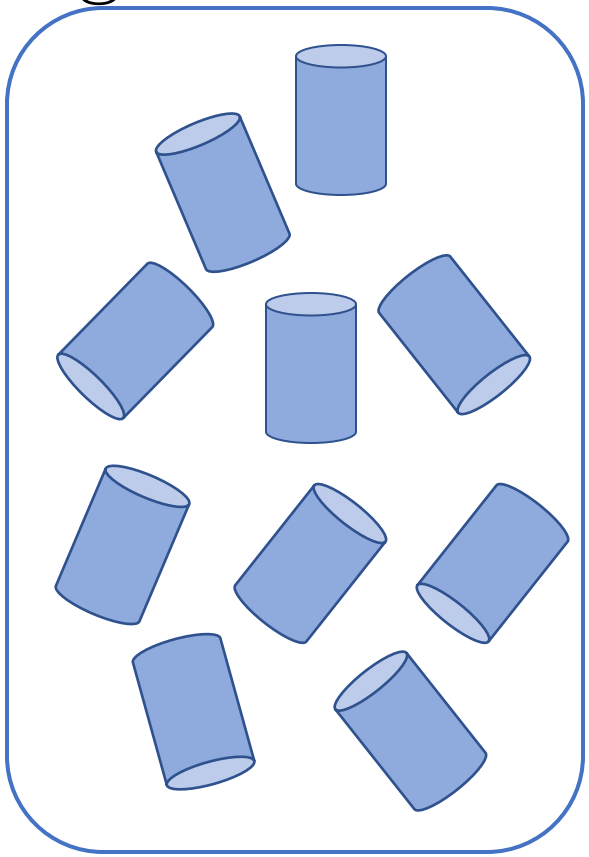
Measurement results in stable regular ROI



Stable regular ROI

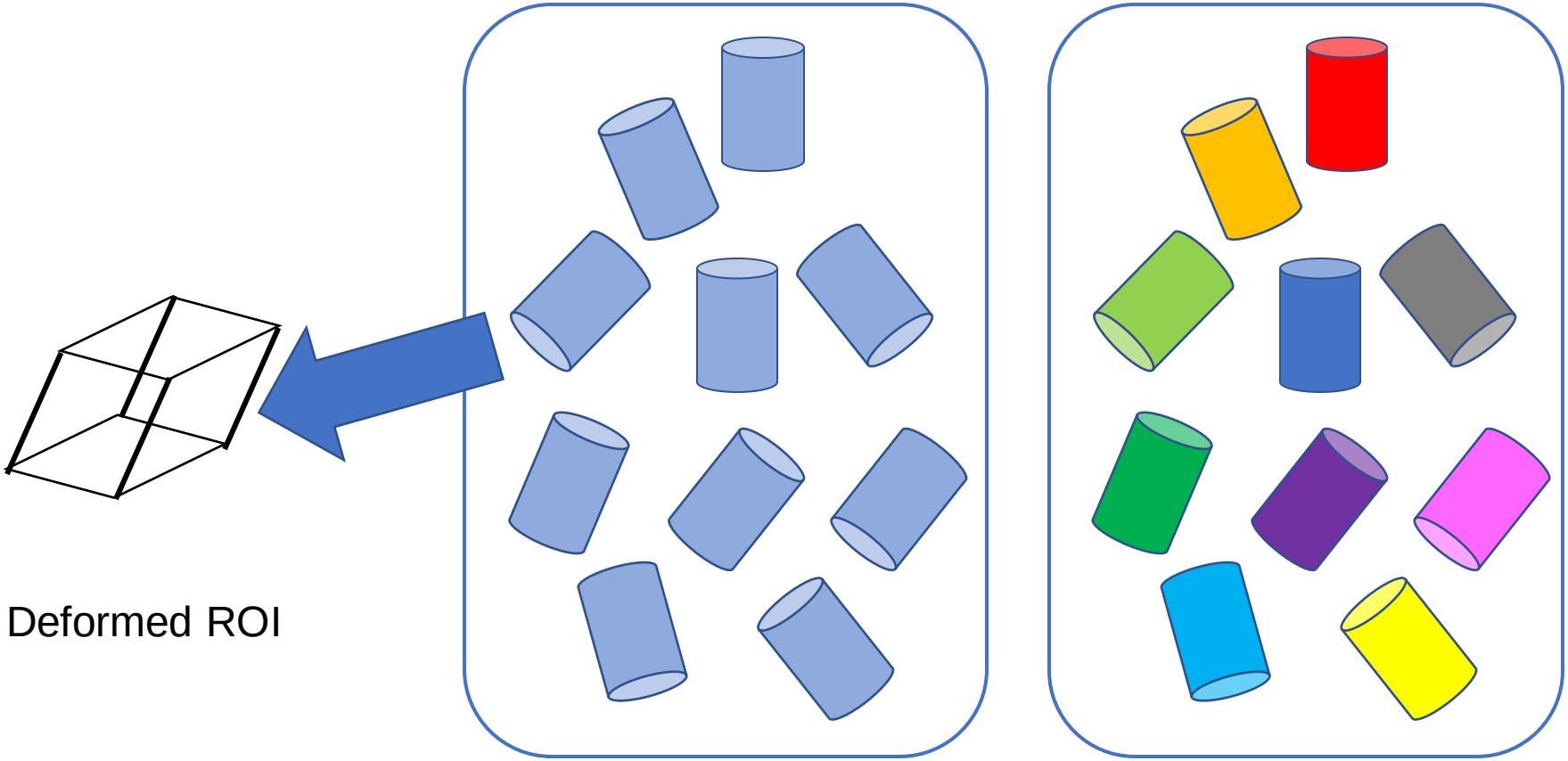


The same workpiece measured in different orientations



Uniform measurement result: size, angle, form

Measurement results in deformed ROI

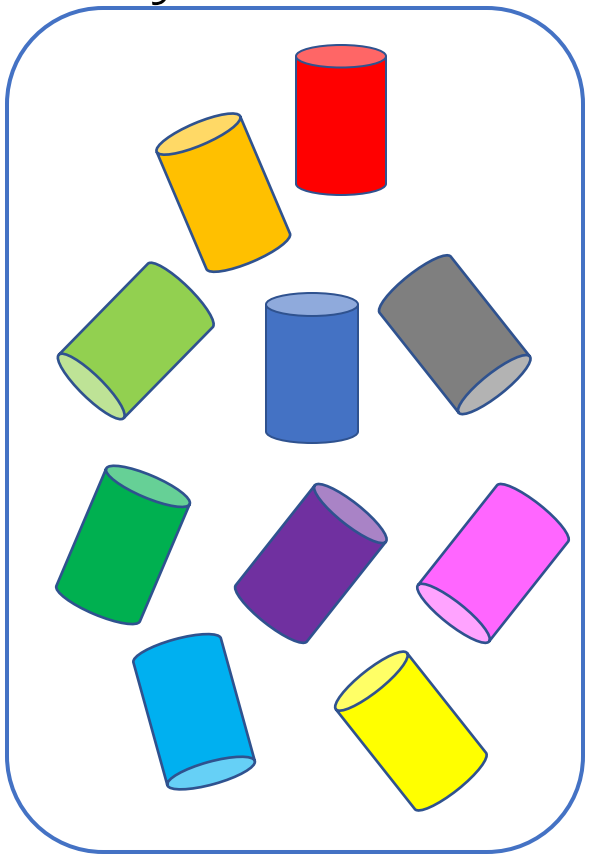


Deformed ROI

The same workpiece measured in different orientations

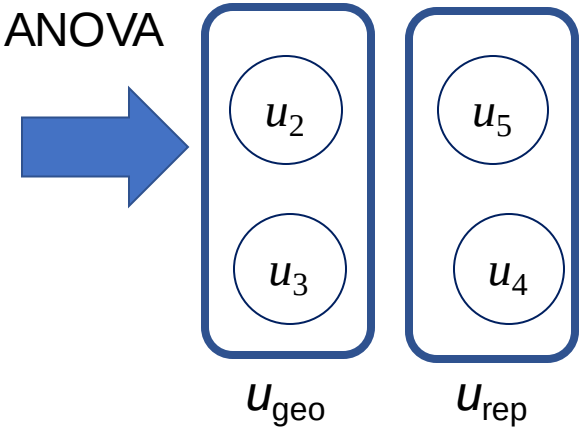
Varied measurement results: size, angle, form

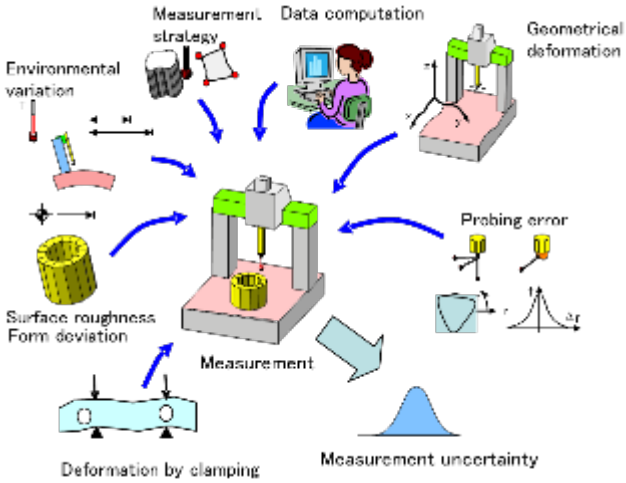
Systematic/random errors in deformed ROI



Variation of measurement results
Bias of measurement results

ANOVA





Combined effect of uncertainty contributors

Uncertainty modules:

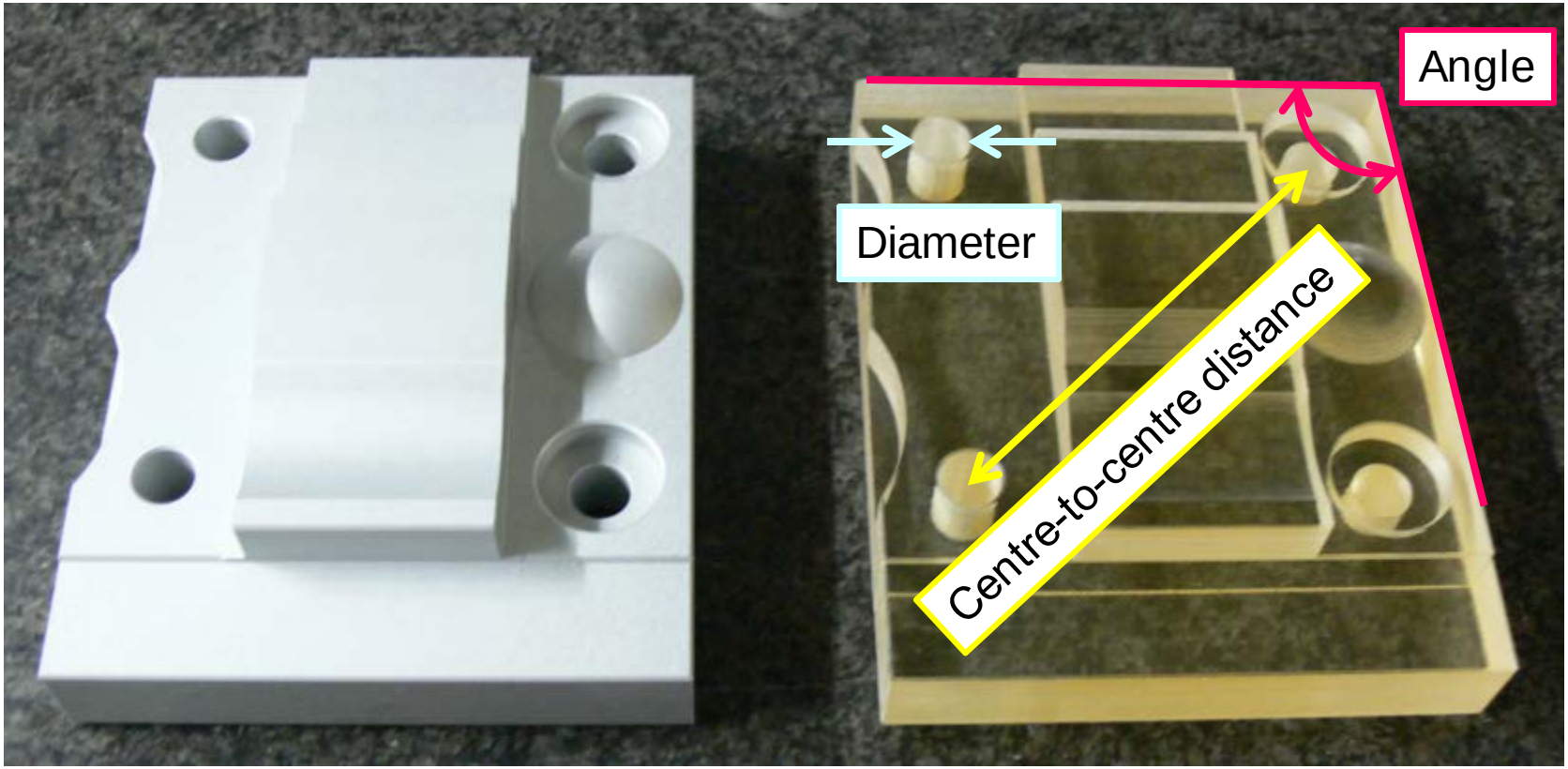
- systematic error
- random error

Required measurements for uncertainty evaluation

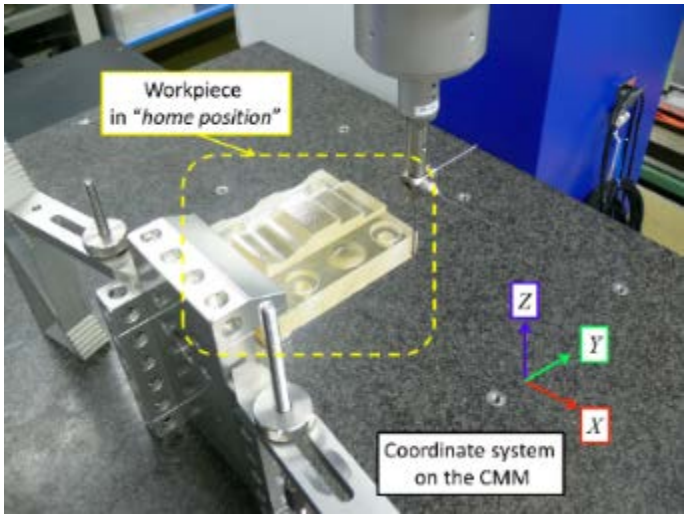
- Measurement of the workpiece
  - 4 orientations
  - 3 repetitions
- Measurement of the length standards
  - along X, Y and Z axes,
  - 3 repetitions
- Measurement of the reference sphere
  - using all styli, which are used in the series of measurement in 4 orientations
  - 3 repetitions

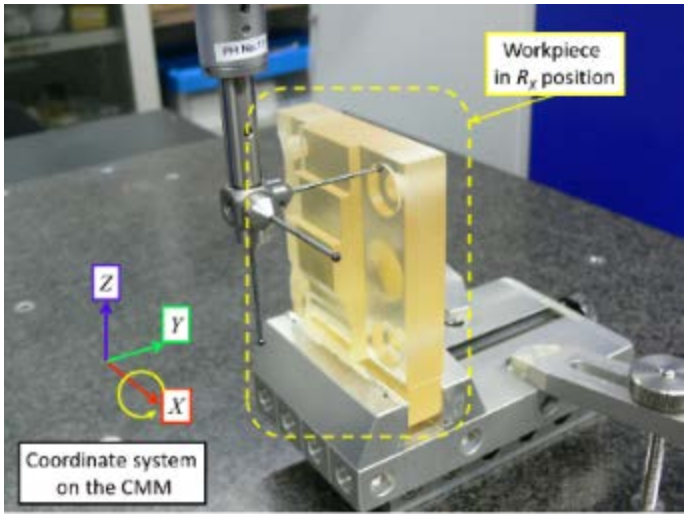
Practice

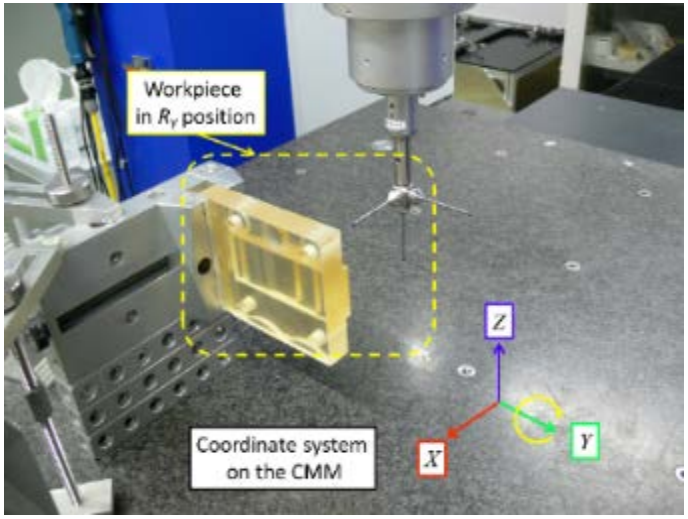
- Angle and distance/size measurement



3 repetitive measurements in 4 orientations







4-orientation is sufficient

Measurement results

	Orientation 1 (home position)	Orientation 2 (R_X position)	Orientation 3 (R_Y position)	Orientation 4 (R_Z position)
Cycle 1	89.9859	90.0140	90.0159	89.9848
Cycle 2	89.9853	89.9860	90.0166	90.0148
Cycle 3	89.9853	89.9862	90.0162	90.0144
$\overline{{}^{j}y}$	89.9855	89.9954	90.0162	90.0047
$\bar{\bar{y}}$	90.0005			

Variation by random errors and short-term system variation

Variation by global errors and long-term system variation

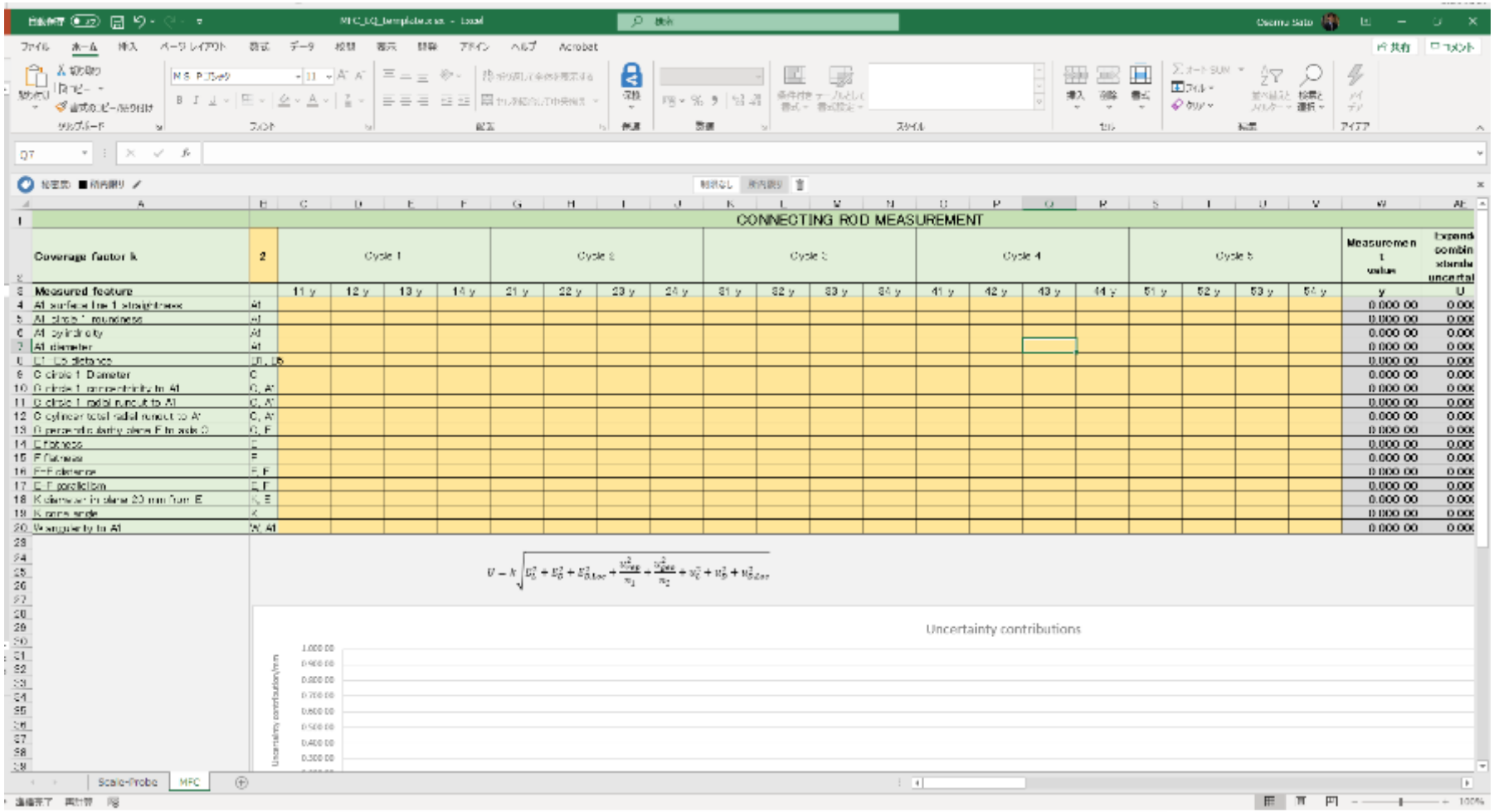
Uncertainty evaluation

Do I need to execute such a complicated computation?

No!

S	DOF	Variance	Expectation of the variance
$S_A = \sum_{i=1}^{n_1}\sum_{j=1}^{n_2}\left(\overline{{}^{j}y} - \bar{\bar{y}}\right)^2 = 0.001548$	$f_A = n_2 - 1 = 3$	$V_A = S_A/f_A = 0.000516$	$u_{rep}^2 + n_1 \cdot u_{geo}^2 = u_{rep}^2 + 3u_{geo}^2$
$S_e = \sum_{i=1}^{n_1}\sum_{j=1}^{n_2}\left({}^{ij}y - \overline{{}^{j}y}\right)^2 = 0.001112$	$f_e = (n_1 - 1)\cdot n_2 = 8$	$V_e = S_e/f_e = 0.000139$	u_{rep}^2
$S = \sum_{i=1}^{n_1}\sum_{j=1}^{n_2}\left({}^{ij}y - \bar{\bar{y}}\right)^2 = 0.002659$	$f = n_1 \cdot n_2 - 1 = 11$		
$u_{rep}^2 = V_e = 0.000139$			
$u_{geo}^2 = (V_A - V_e)/n_1 = 0.000126$			
$U = k \cdot \sqrt{\frac{u_{rep}^2}{n_1} + \frac{u_{geo}^2}{n_2}} = 3\sqrt{\frac{0.000139}{3} + \frac{0.000126}{4}} = 0.0264$			

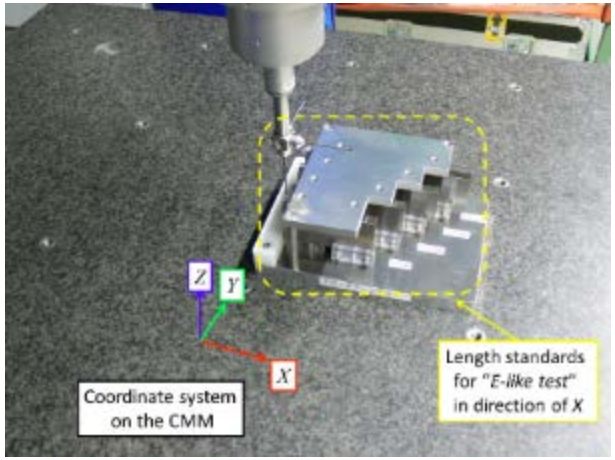
Calculation with spread sheet software

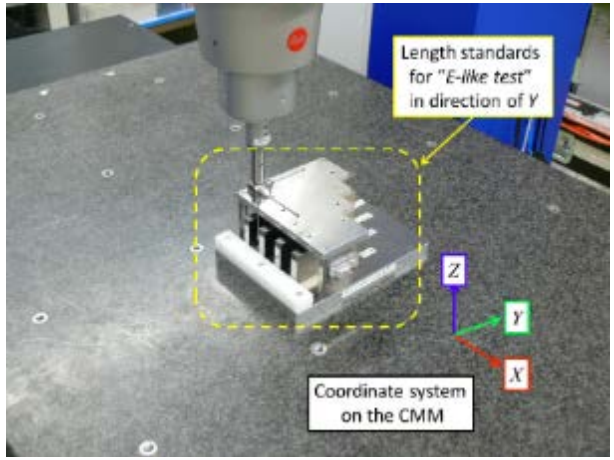


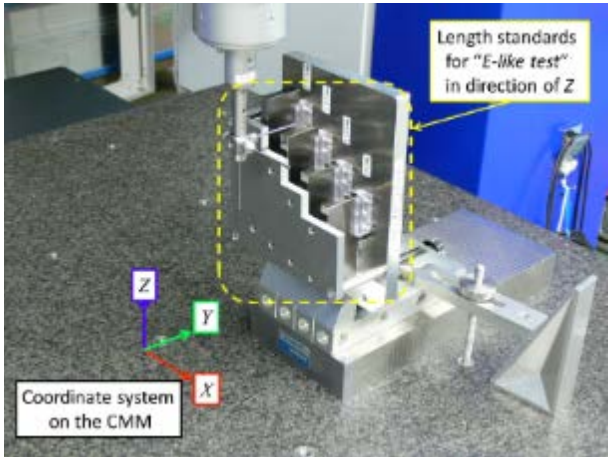
Excellent template provided by EUCoM project

Additional measurement

- Length standards are measured in *X*, *Y* and *Z* directions.
  - Evaluate the averaged scale error in ROI
  - When performing the compensation, the single value is applied for any measurement directions.



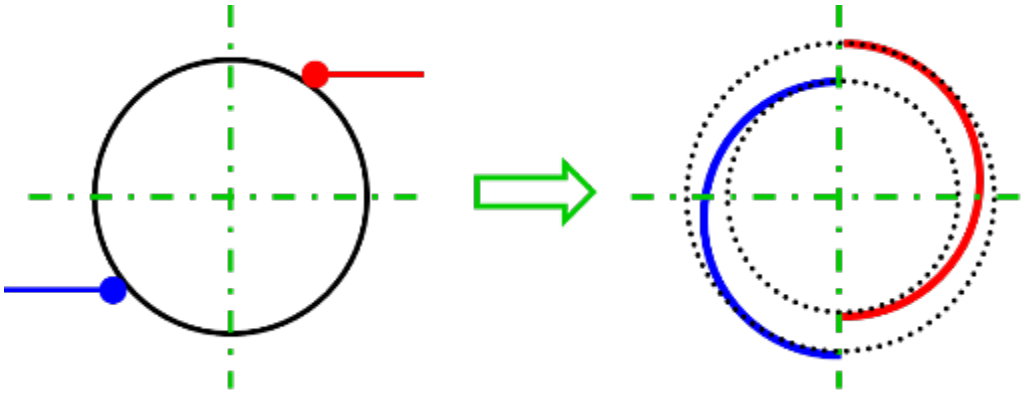




Systematic error by using multi styli

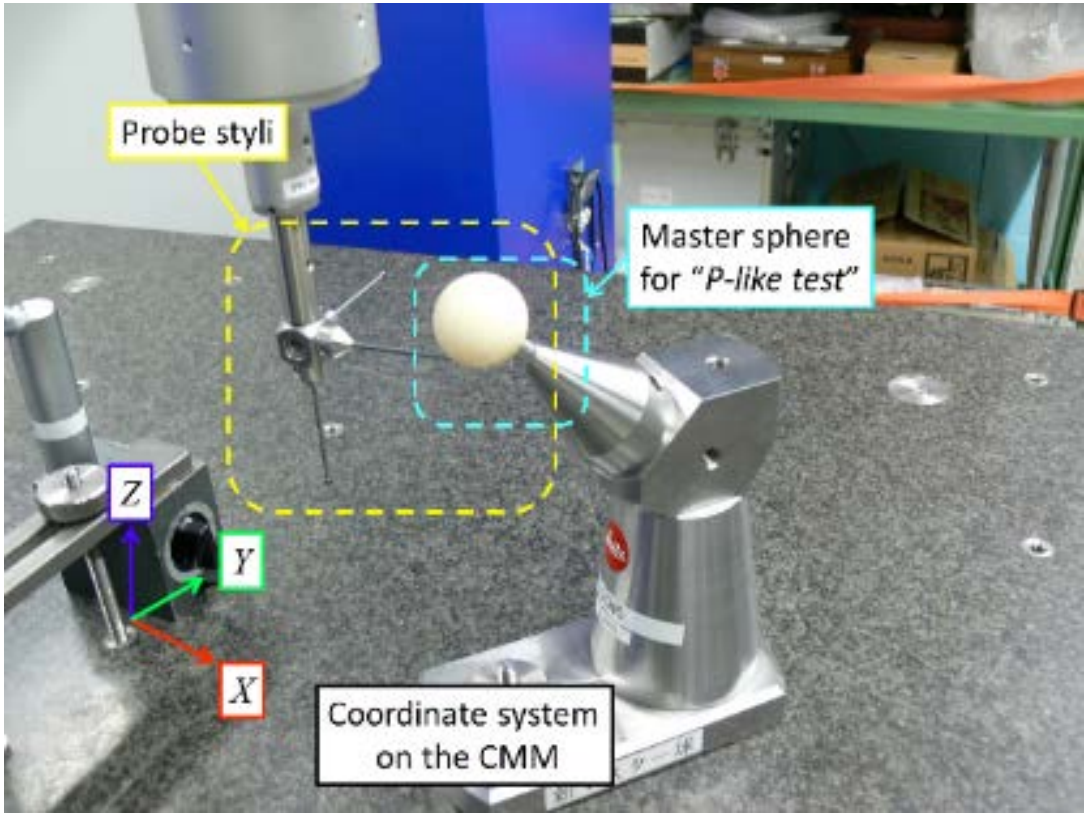
- Quasi-systematic error derived by probe stylus location error

- Quasi-systematic error derived by probe size error

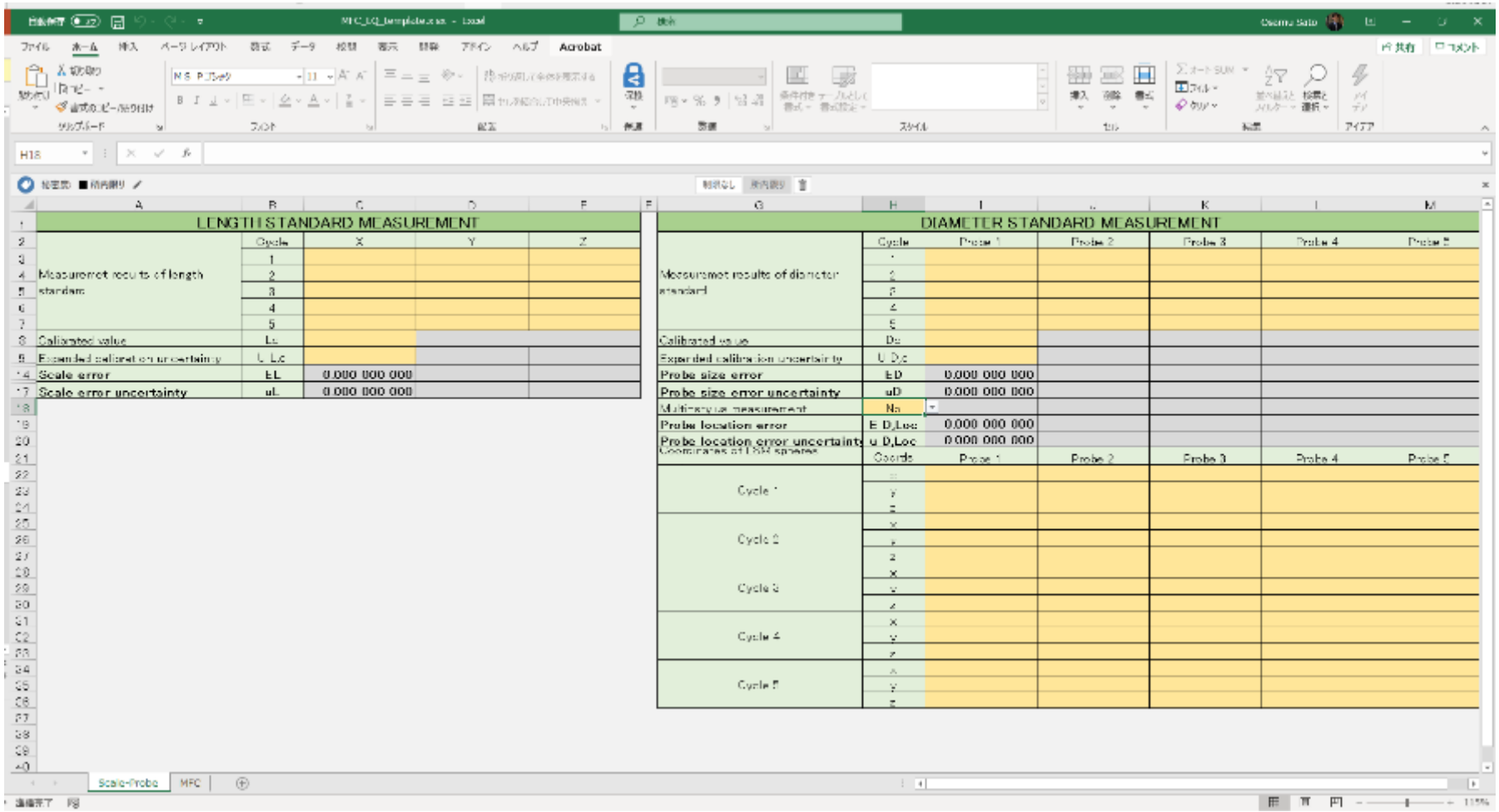


Additional measurement

- Master sphere is measured to estimate the probing errors.



Calculation with spread sheet software



LENGTH STANDARD MEASUREMENT

	Cycle	X	Y	Z
Measurement results of length standard	1			
	2			
	3			
	4			
	5			
Calibrated value	Lc			
Expanded calibration uncertainty	U_Lc			
Scale error	EL	0.000 000 000		
Scale error uncertainty	uL	0.000 000 000		

DIAMETER STANDARD MEASUREMENT

	Cycle	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5
Measurement results of diameter standard	1					
	2					
	3					
	4					
	5					
Calibrated value	Dc					
Expanded calibration uncertainty	U_Dc					
Probe size error	ED	0.000 000 000				
Probe size error uncertainty	uD	0.000 000 000				
Multiple measurement	Nm					
Probe location error	E_D,Loc	0.000 000 000				
Probe location error uncertainty	u_D,Loc	0.000 000 000				

Coordinates of CMM spheres

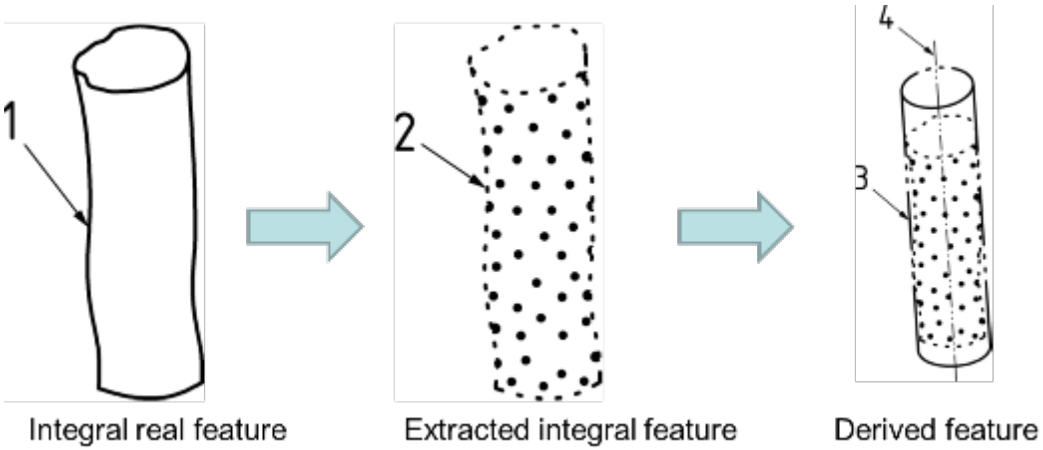
	Coords	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5
Cycle 1						
	Y					
	Z					
Cycle 2	X					
	Y					
	Z					
Cycle 3	X					
	Y					
	Z					
Cycle 4	X					
	Y					
	Z					
Cycle 5	X					
	Y					
	Z					

Excellent template provided by EUCoM project

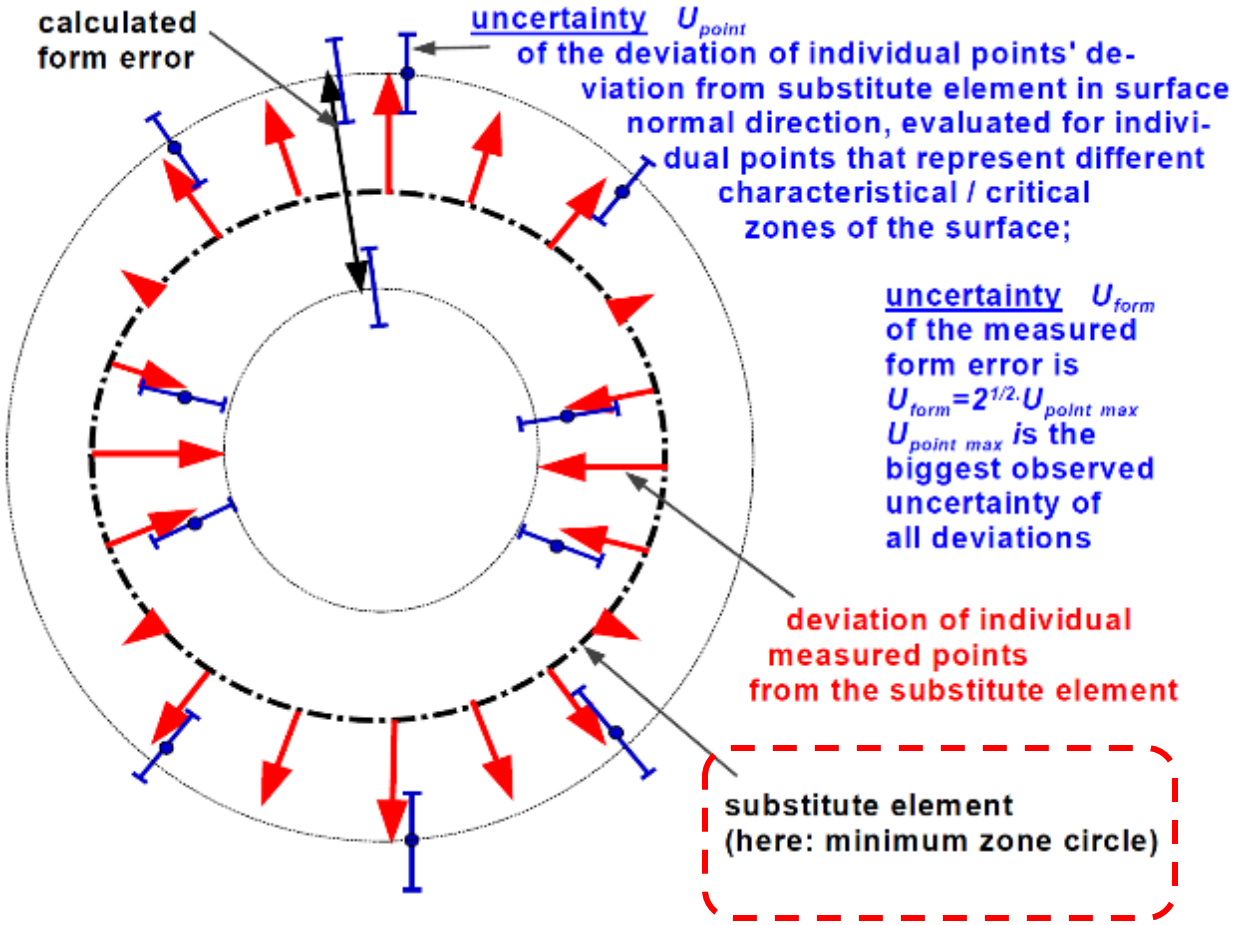
Form evaluation

- Form error of the feature is evaluated
  - not as that of the integral real feature,
  - but as that of the feature associated with the designated extracted measured points

- Uncertainty of the form error measurement is estimated related with the distribution of the designated measurement points.



Basic idea: form error meas.



Uncertainty of form error measurement

Uncertainty of point deviation

Data to be required for evaluation

Pla_3		Home ☒os	Rx	Ry	Rz
n1	n7/n2	1	2	3	4
1	1	0.0029	0.0026	0.0007	0.0009
	2	0.0006	0.0005	-0.0001	0.0007
	...	...	...	...	...
	12	-0.0019	-0.0021	-0.0012	-0.0008
2	1	0.0020	0.0021	0.0007	0.0003
	2	0.0003	0.0003	-0.0002	0.0002
	...	...	...	...	...
	12	-0.0017	-0.0019	-0.0013	-0.0008
3	1	0.0015	0.0019	0.0008	0.000
	2	0.0000	0.0002	-0.0002	0.000
	...	...	...	...	...
	12	-0.0015	-0.0019	-0.0012	-0.0007

Deviations for respective points

Is the data available?

Output from CMM software

Depending on the software

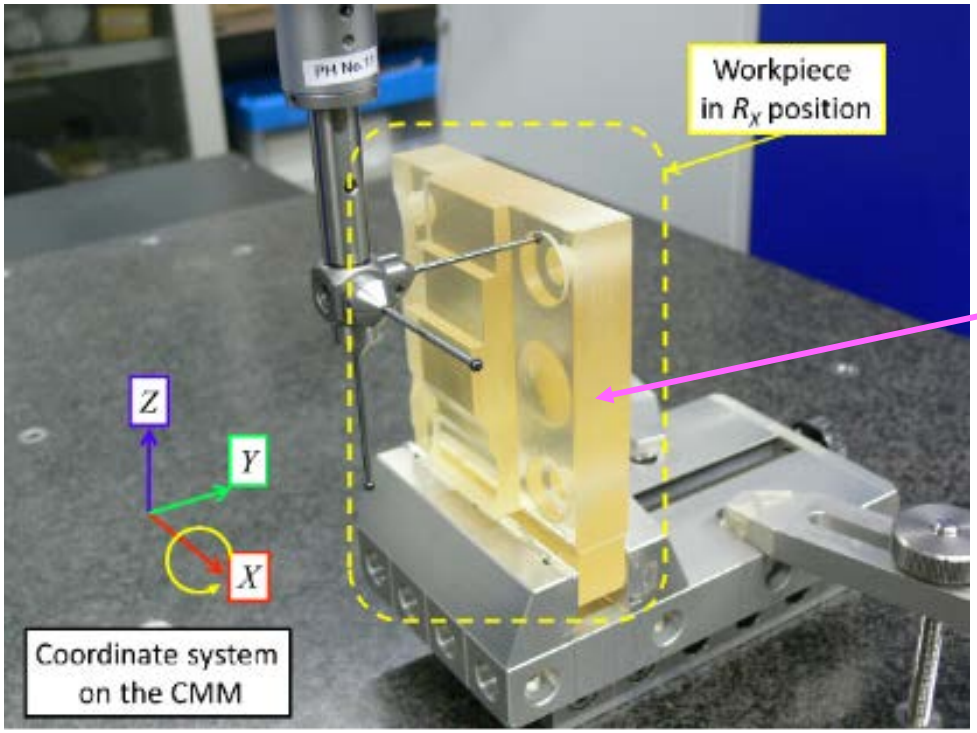
1. Form error value only
2. Form error value and limited information
   - Maximum/minimum deviation
   - standard deviation of the distribution of extracted points
3. Form error value and full information
   - respective deviations from the associated feature

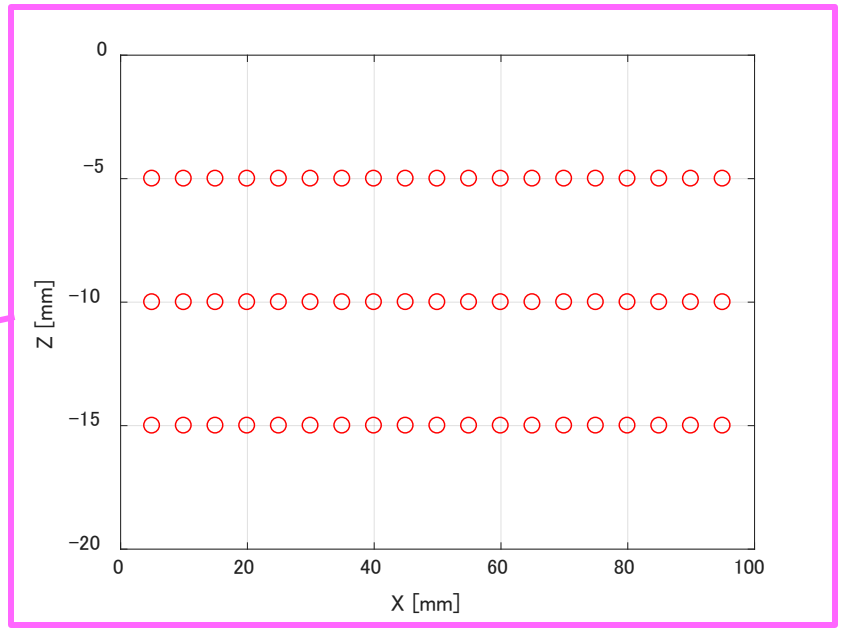
Note

- The full information is stored as internal parameters in the software.
  - Whether the operator can access the internal parameters or not depends on the software.

- For practical use in industrial floors, the uncertainty estimation should be executable with poor information:
  - the value of form error itself and number of measurement points, at least.

Example: plane measurement





57 measurement points
Orthogonal grid sampling
4 positions
3 times repetition

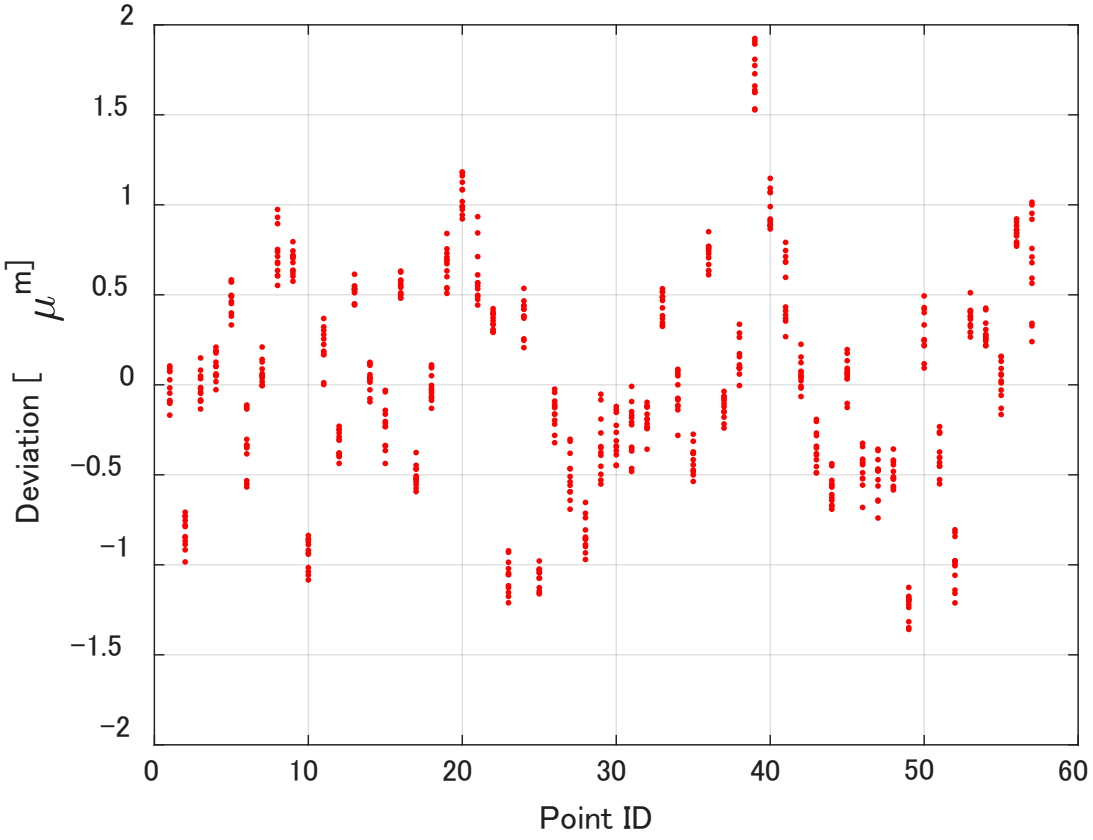
Uncertainty evaluation using full information

- Flatness measurement result in μm

	Home position	Rx	Ry	Rz
1st	2.8	2.9	3.1	3.2
2nd	2.8	2.9	3.1	3.0
3rd	2.9	2.9	2.9	3.0

Flatness of the plane derived from the designated 57 points is 3.0 μm

Uncertainty evaluation using full information



		n1	n2	n3
A1	B1	−0.0012	−0.00118	−0.00124
	B2	−0.00114	−0.00098	−0.00098
	B3	−0.00112	−0.00105	−0.00105
	B4	−0.00107	−0.00115	−0.00116
	B5	−0.00094	−0.00092	−0.00093
	B6	−0.00085	−0.00085	−0.00086
	B7	−0.00073	−0.00089	−0.00098
	B8	−0.00057	−0.00067	−0.00061
	B9	−0.00053	−0.00048	−0.00056
	B10	−0.00052	−0.00051	−0.00052

u for single point is 0.11 μm
u for two points is 0.16 μm
U for form meas. is 0.48 μm from 57 points probing

For poor information case

- Estimation of single point deviation uncertainty with the PV value
  - ex.
  - Flatness = 2.8 μm
  - Actual peak/valley = 1.6 μm / -1.2 μm
    - Invisible for the CMM operator
  - Assumed peak/valley = 1.4 μm / -1.4 μm
    - Principle of maximum entropy
    - W/o any information of the distribution of deviation

For poor information case

- Data for analysis with the assumption

		n1	n2	n3
A1	B1	−0.0014	−0.0014	−0.0014
	B2	0.0014	0.0014	0.0014
A2	B1	−0.0014	−0.0014	−0.0014
	B2	0.0014	0.0014	0.0014
A3	B1	−0.0016	−0.0016	−0.0015
	B2	0.0016	0.0016	0.0015
A4	B1	−0.0016	−0.0015	−0.0015
	B2	0.0016	0.0015	0.0015

Executable with any CMMs

Executable for any form

u for single point is 0.09 μm
u for two points is 0.13 μm
U for form meas. is 0.39 μm from 2 points data

Might be under estimation

For poor information case

- Input actually observed PV values

		n1	n2	n3
A1	B1	0.0016	0.0016	0.0016
	B2	−0.0012	−0.0012	−0.0012
A2	B1	0.0017	0.0015	0.0015
	B2	−0.0012	−0.0014	−0.0013
A3	B1	0.0019	0.0019	0.0017
	B2	−0.0012	−0.0012	−0.0012
A4	B1	0.0019	0.0018	0.0018
	B2	−0.0013	−0.0012	−0.0012

Executable with several CMMs

Executable for any form

u for single point is 0.13 μm
u for two points is 0.18 μm
U for form meas. is 0.54 μm

Good estimation

Summary

- Uncertainty evaluation for dimensional measurement using CMM is developed

- Solution proposal: a posteriori method w/o special materials
  - Multiple measurement
  - ANOVA

- Feature: executable in ordinal industrial floor
  - Operation is executable with ordinal CMM
  - Additional measurement is needed, but without special equipment
  - Uncertainty is computable with spread sheet software
    - Calculation template is provided

A posteriori method is available!

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EMPIR EURAMET

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