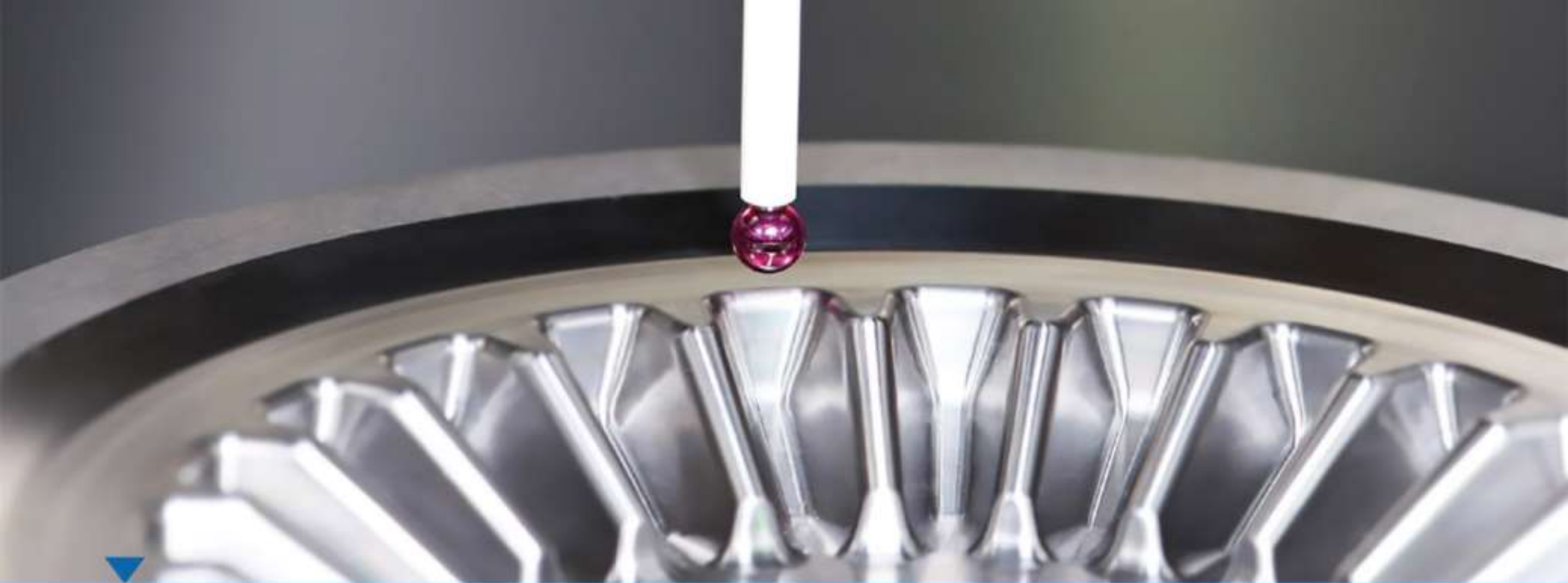

EMRP JRP IND62 –TIM: Use of on-board metrology systems for area-scanning on machine tools

CZECH METROLOGY INSTITUTE

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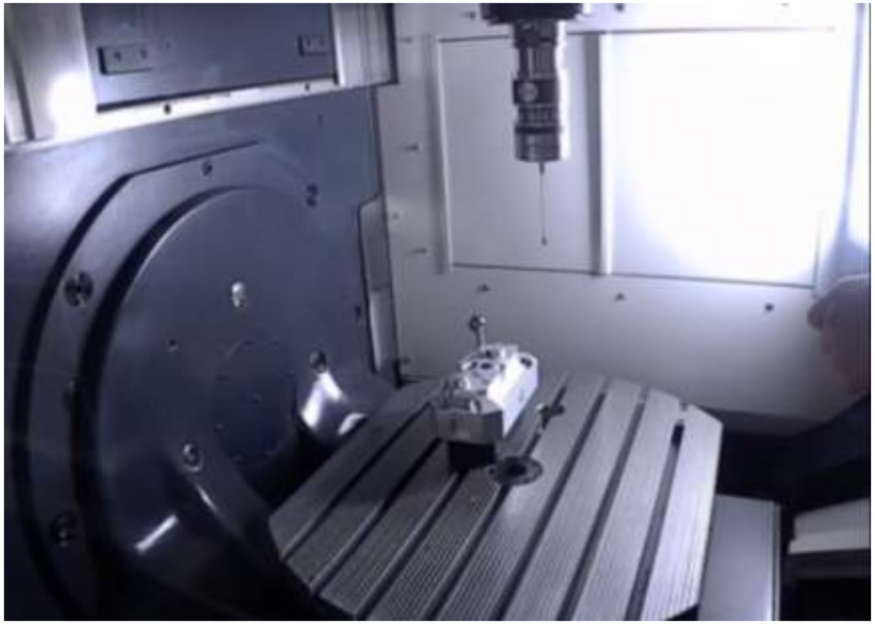
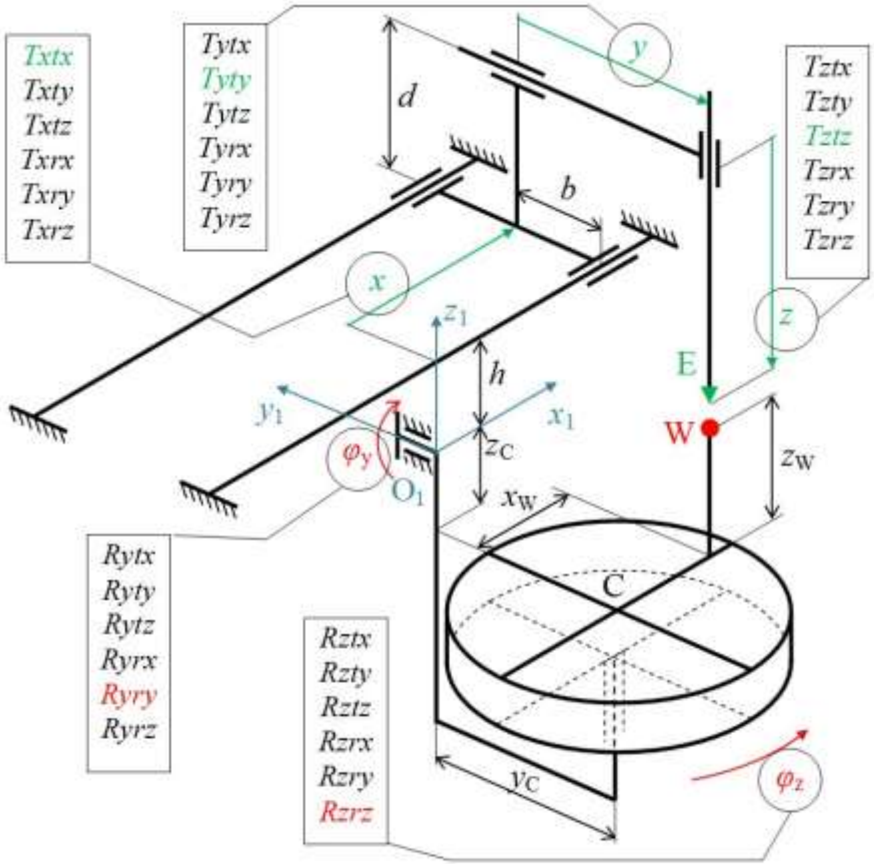
Pavel Skalník
Jaromír Hynek

- **CNC MACHINE TOOL**
- **FREEFORM STANDARD**
- **SCANING**
- **ON-BOARD METROLOGY**
- **INTERCOMPARISON**
- **E_n CRITERION**

- **CNC MACHINE TOOL**
- FREEFORM STANDARD
- SCANING
- ON-BOARD METROLOGY



MODEL OF CNC MACHINE TOOL



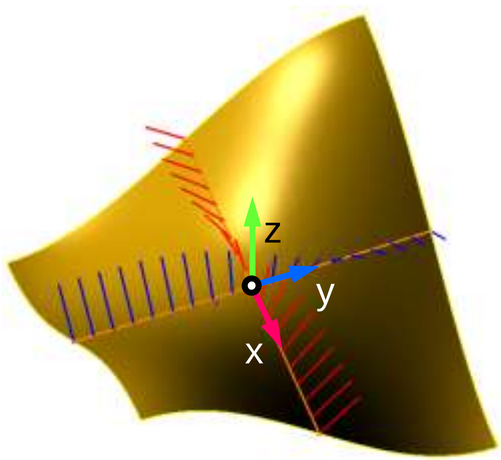
Double-sine PTB freeform standard

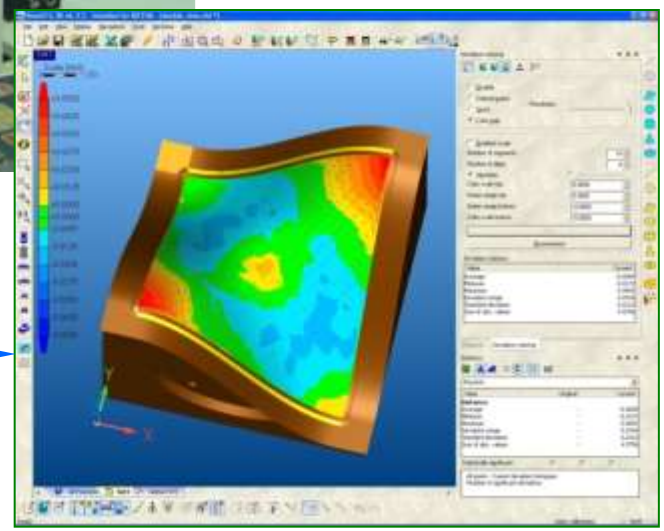
- CNC MACHINE TOOL
- **FREEFORM STANDARD**
- SCANING
- ON-BOARD METROLOGY

MATHEMATICAL MODEL

$$z(x,y)=\sin(x)\sin(y)$$

CAD MODEL





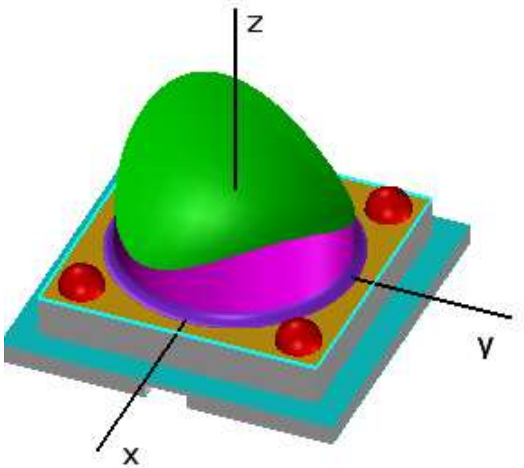
CMI Hyperbolic paraboloid freeform standard

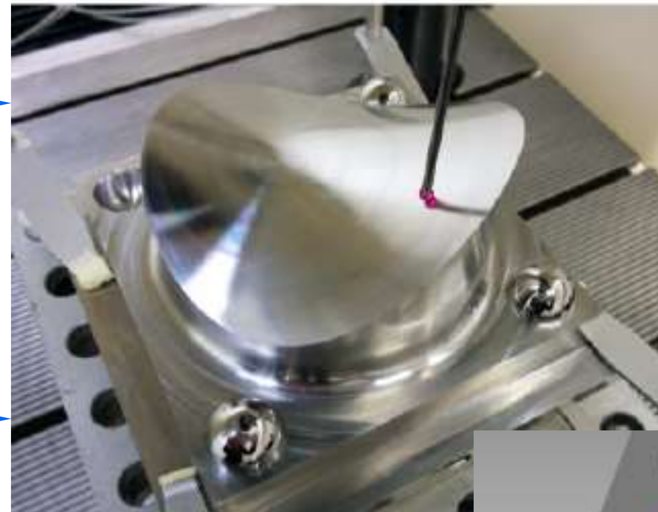
- CNC MACHINE TOOL
- **FREEFORM STANDARD**
- SCANING
- ON-BOARD METROLOGY

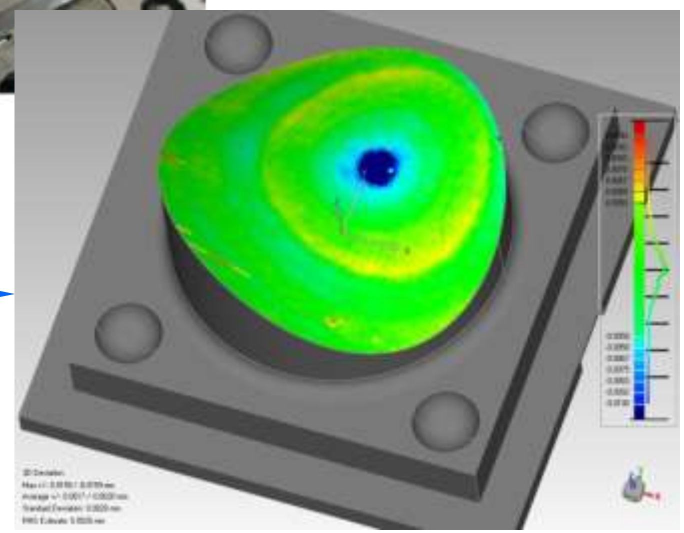
MATHEMATICAL MODEL

$$z(x,y) = x \cdot y$$

CAD MODEL





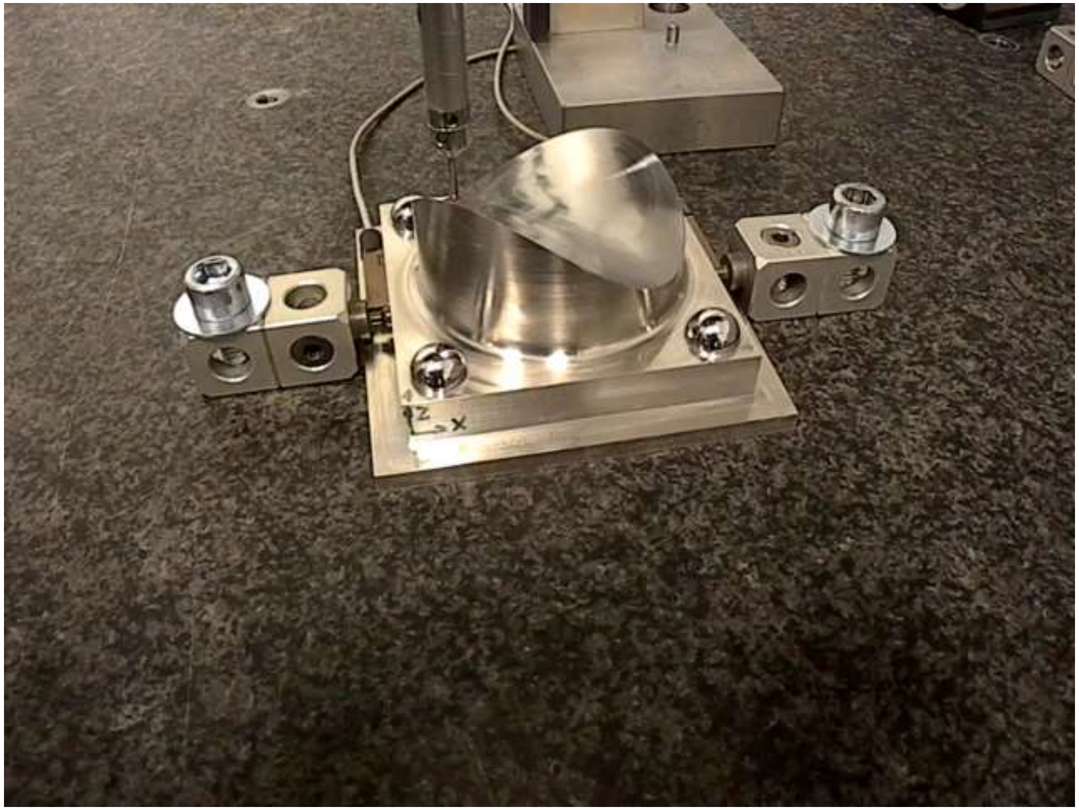


Scanning

- CNC MACHINE TOOL
- FREEFORM STANDARD
- SCANING
- ON-BOARD METROLOGY

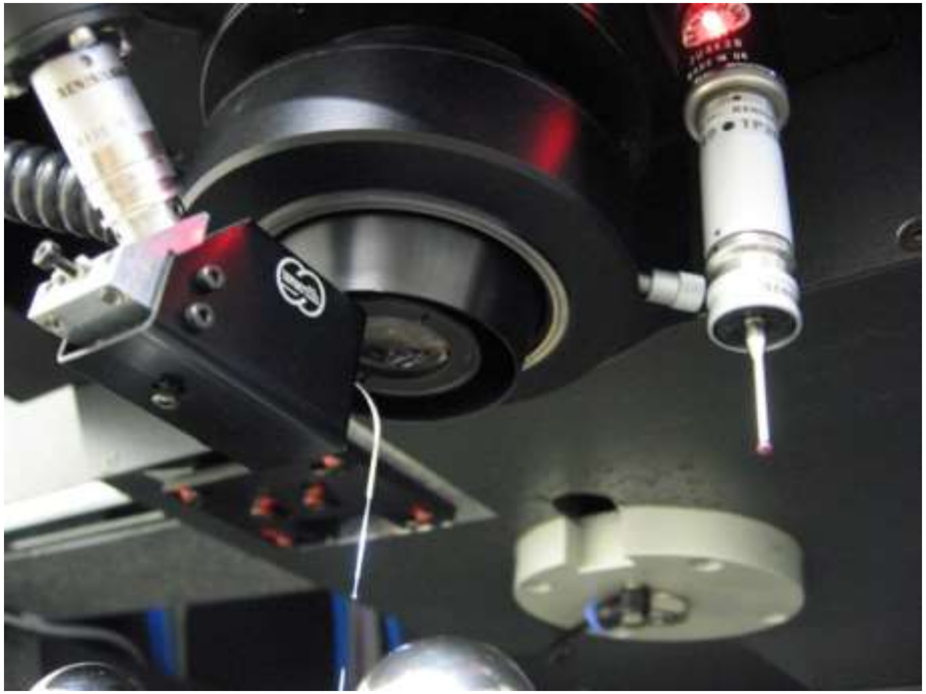
CONTACT SCANNING

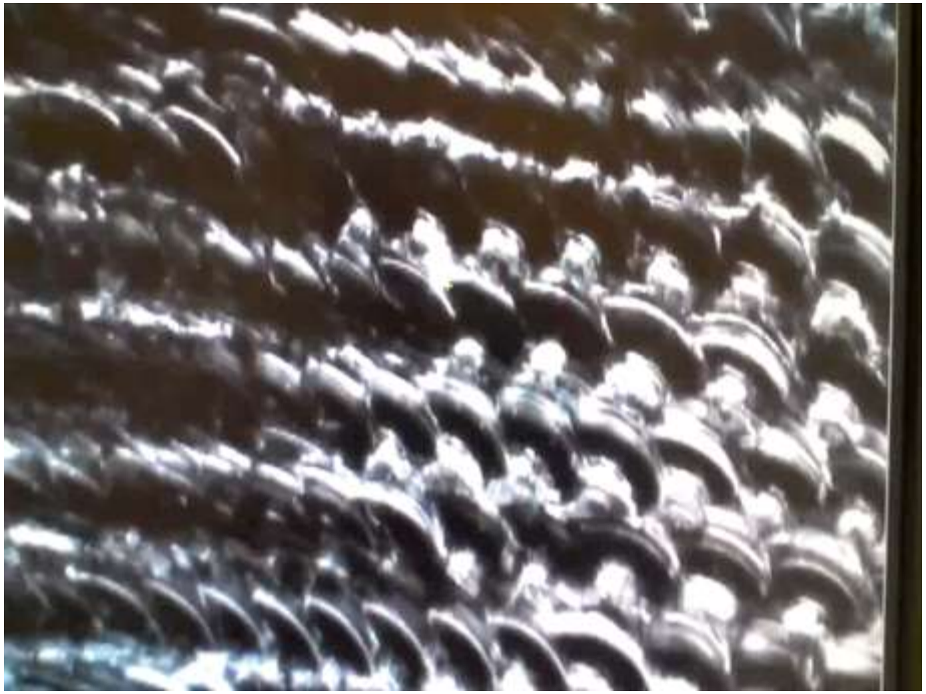
(e.g. ZEISS PRISMO with active scanning probe VAST)



- CNC MACHINE TOOL
- FREEFORM STANDARD
- SCANING
- ON-BOARD METROLOGY

LASER SCANNING
(e.g. based on autofocus)





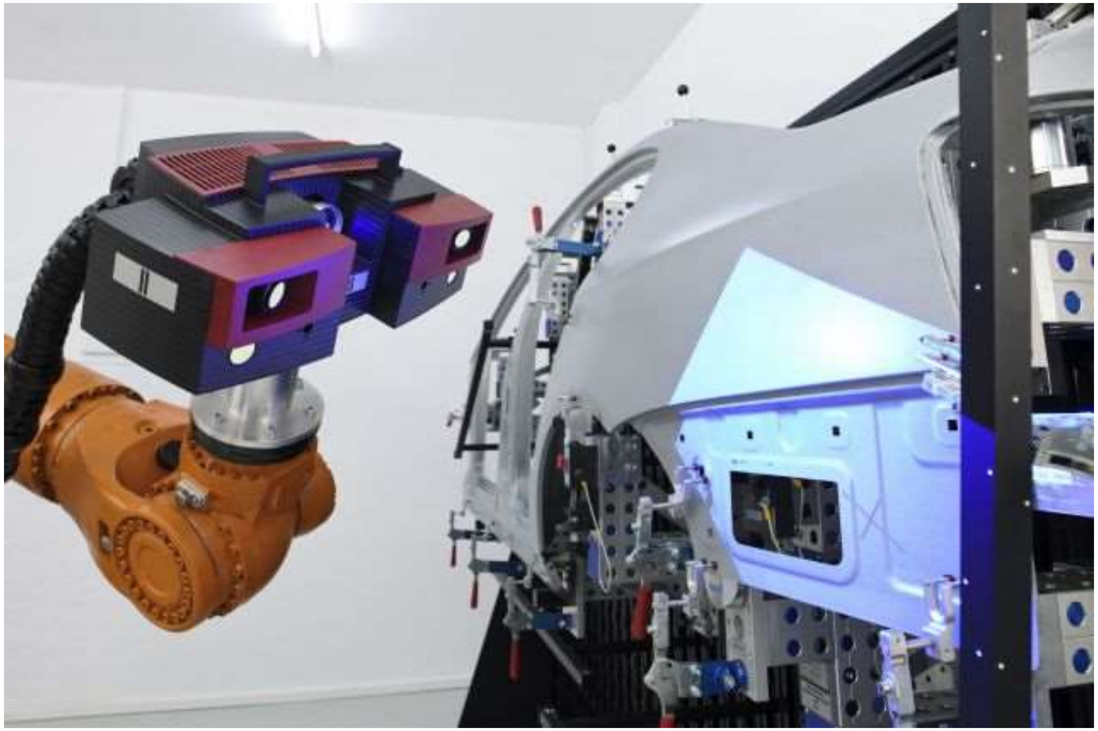
- CNC MACHINE TOOL
- FREEFORM STANDARD
- **SCANING**
- ON-BOARD METROLOGY

LASER SCANNING

(e.g. based on autofocus)

- CNC MACHINE TOOL
- FREEFORM STANDARD
- SCANING
- ON-BOARD METROLOGY

AREA SCANNING – PHOTOGRAMMETRY

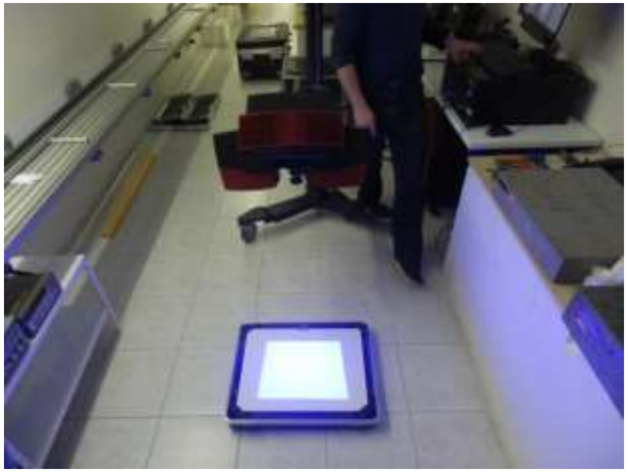


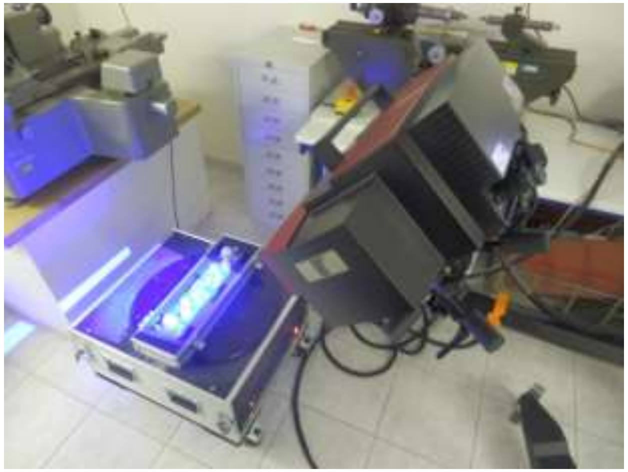
VDI/VDE 2634 Part 2 - *Optical 3-D measuring systems - Optical systems based on area scanning*

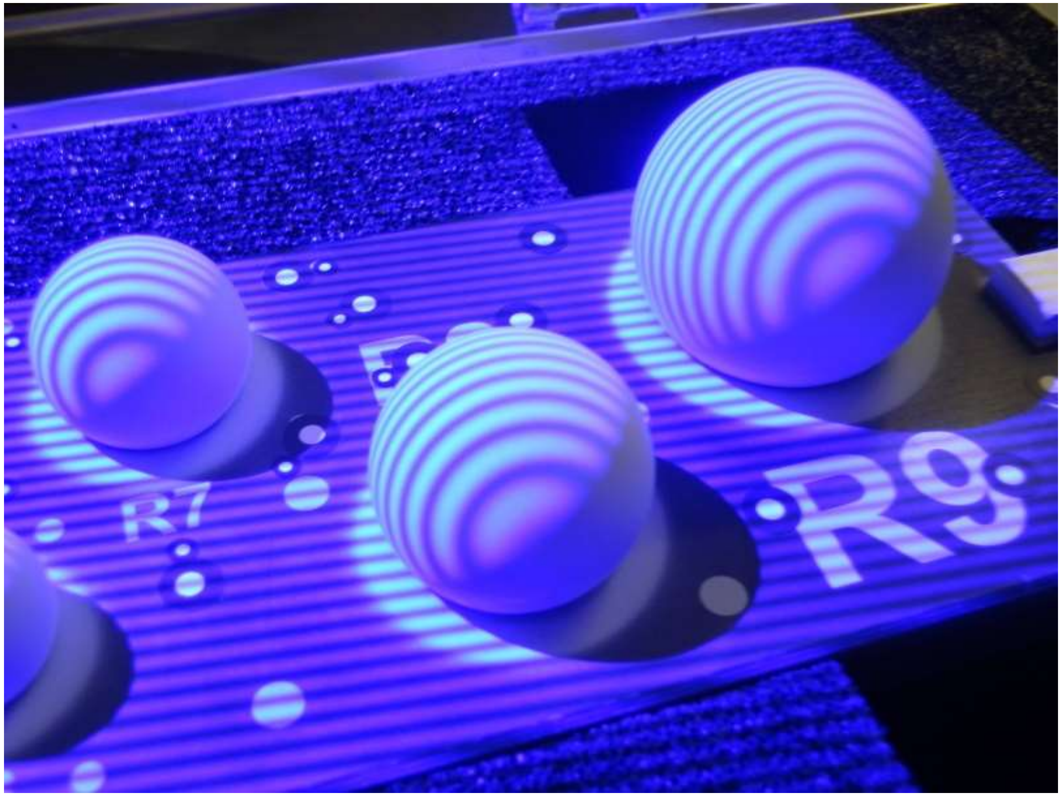
VDI/VDE 2634 Part 3 - *VDI/VDE 2634 Part 3 Optical 3D-measuring systems - Multiple view systems based on area scanning*

- CNC MACHINE TOOL
- FREEFORM STANDARD
- **SCANING**
- ON-BOARD METROLOGY

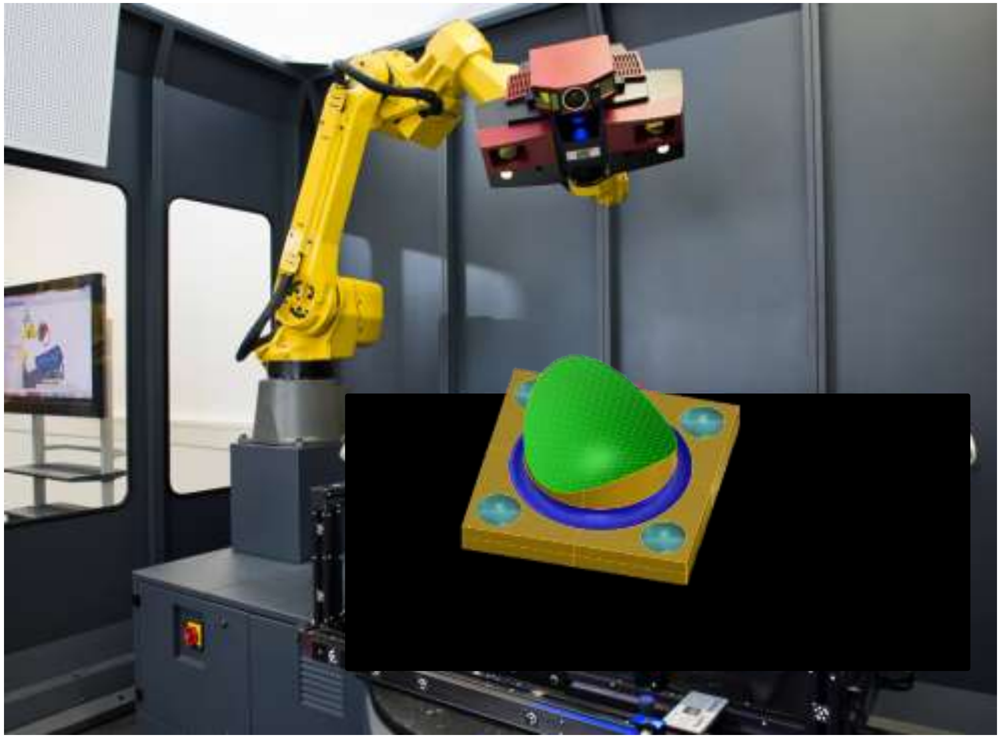
Fringe projection





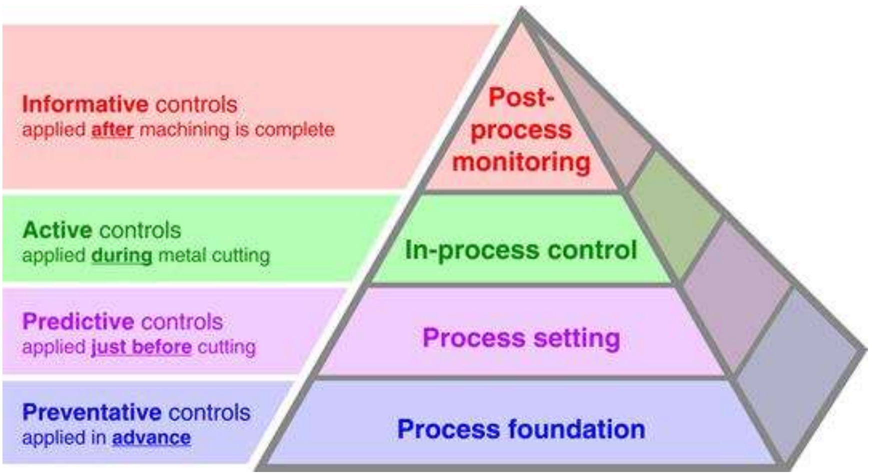


- CNC MACHINE TOOL
- FREEFORM STANDARD
- SCANING
- **ON-BOARD METROLOGY**



Demonstration – measurement of FF-MS on machine tool Deckel Maho DMU 50 with Renishaw probe OMP 400

Productive Process Pyramid™
(acc. Metrology solutions for productive process control, Brochure of Renishaw)



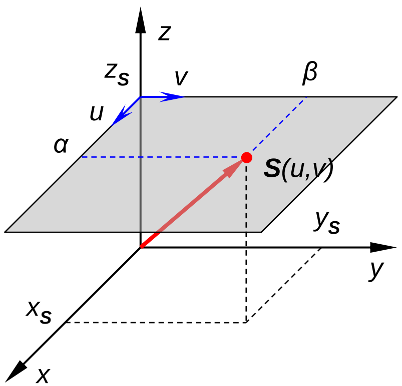
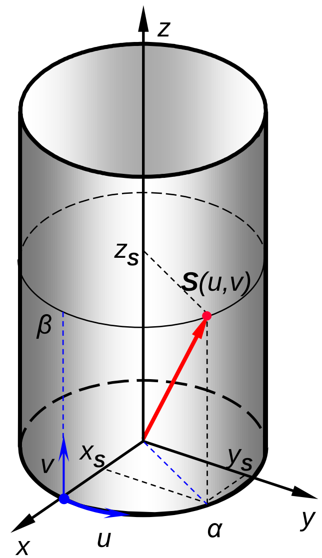
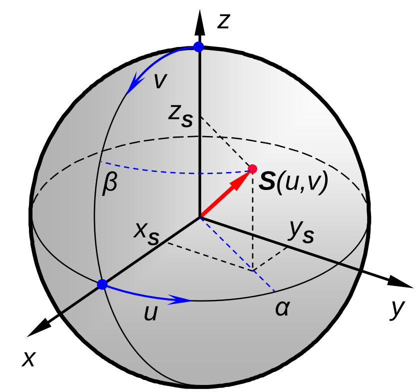
In-process control is represented by active controls applied during metal cutting. The control is focused on inherent sources of errors caused during all machining processes, such as tool wear, part deflection and the impact of temperature and heat flows. The in-process control is carried out by on-machine probing module equipped by inspection cycles included in NC programs.

Freeform

- **WHY FREEFORM?**
- **WHY FREEFORM STANDARD?**
- **HOW TO USE FREEFORM STANDARD?**
- **INTERCOMPARISON**
- **E_n CRITERION**

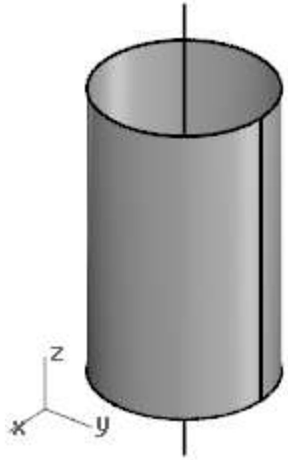
Basic geometrical elements

- **WHY FREEFORM?**
- WHY FREEFORM STANDARD?
- HOW TO USE FREEFORM STANDARD?

Plane	Cylinder	Sphere
		
$ax + by + cz + d = 0$	$x^2 + y^2 = r^2$	$x^2 + y^2 + z^2 = r^2$
Gauge block **Step gauge**	**Hole bar** **Hole plate**	**Ball** **Ball bar** **Ball plate**

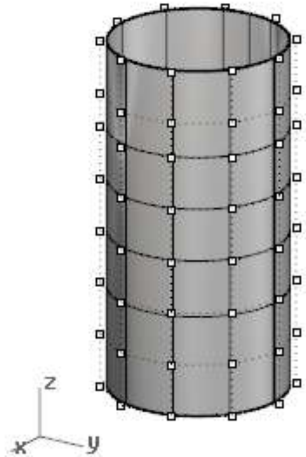
- **WHY FREEFORM?**
- WHY FREEFORM STANDARD?
- HOW TO USE FREEFORM STANDARD?

Cylinder
as a basic
geometrical element

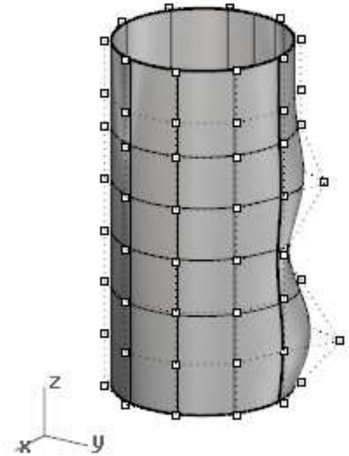


$$x^2 + y^2 = r^2$$

Cylinder
as a freeform geometry
(represented in NURBS)



Freeform shape
(modified cylinder)

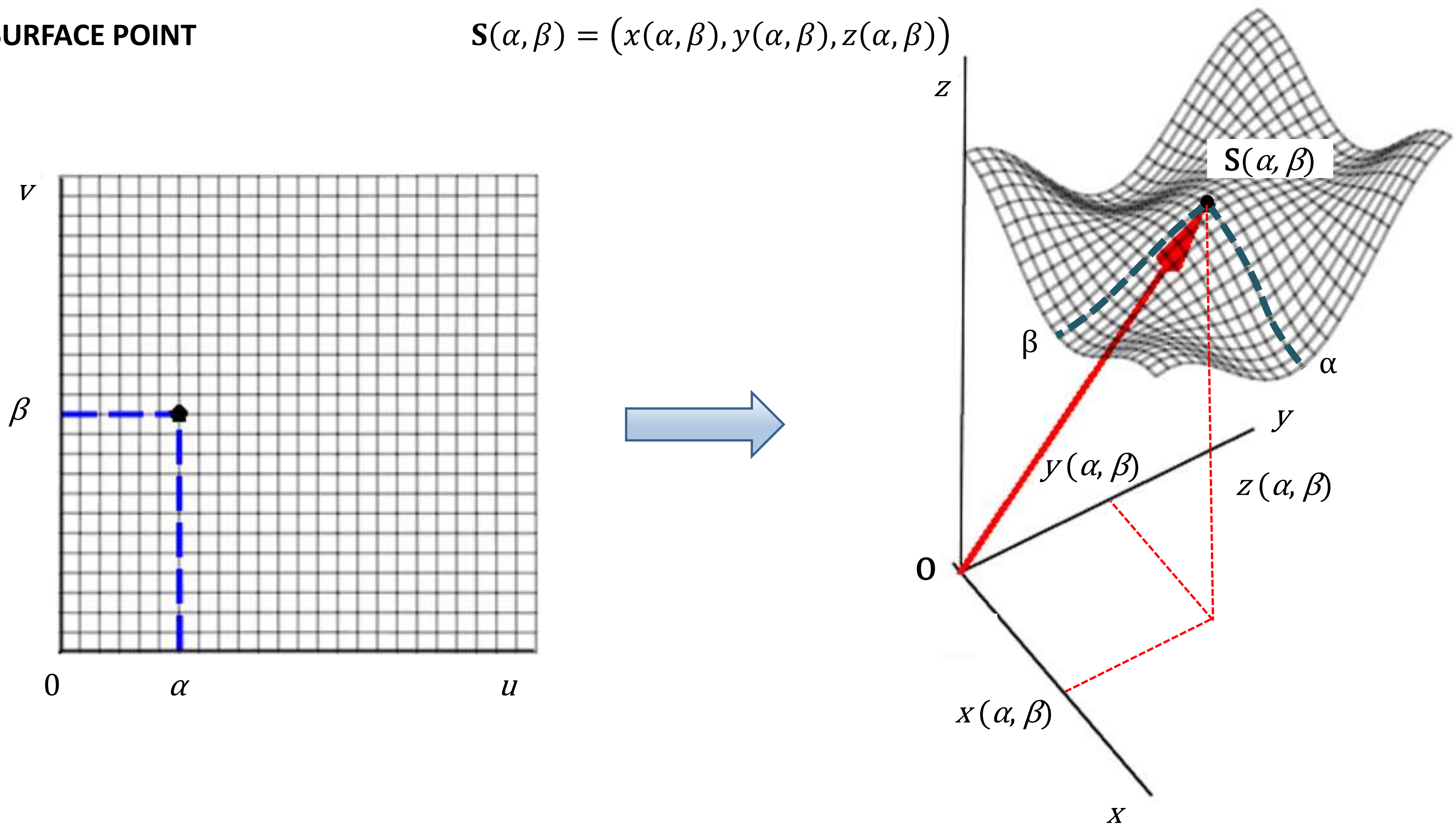


$$\mathbf{S}(u,v) = \sum_{i=0}^{m}\sum_{j=0}^{n} R_{i,j}(u,v)\mathbf{P}_{i,j}, \quad 0 \le u \le 1, \quad 0 \le v \le 1$$

$$R_{i,j}(u,v) = \frac{N_{i,p}(u)N_{j,q}(v)w_i}{\sum_{i=0}^{m}\sum_{j=0}^{n} N_{i,p}(u)N_{j,q}(v)w_i}$$

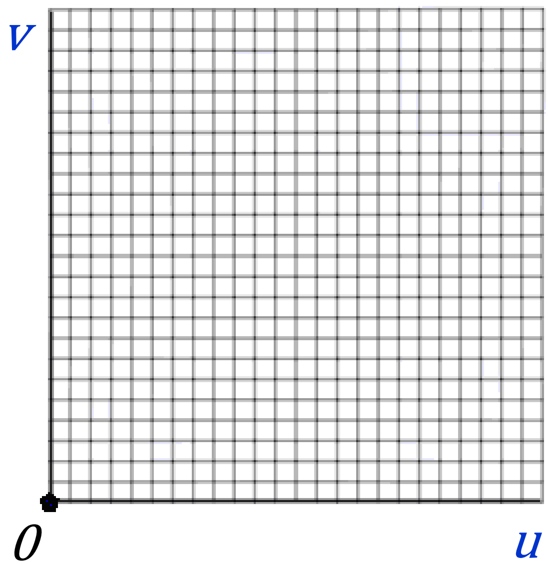
FREE-FORM SURFACE $\mathbf{S}(u,v) = \big(x(u,v), y(u,v), z(u,v)\big)$

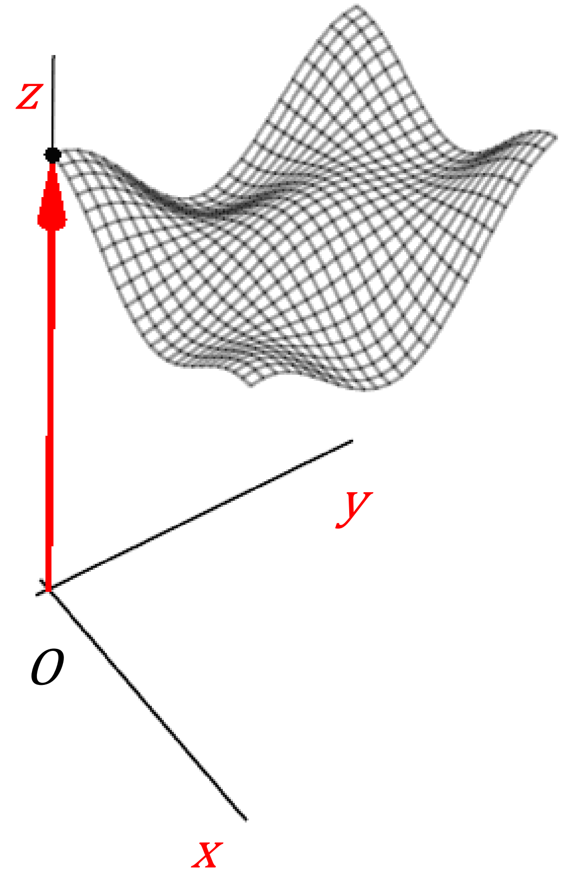
SURFACE POINT $\mathbf{S}(\alpha,\beta) = \big(x(\alpha,\beta), y(\alpha,\beta), z(\alpha,\beta)\big)$



FREE-FORM SURFACE

PARAMETRIC (*u*,*v*) AND CARTESIAN (*x*,*y*,*z*) COORDINATES





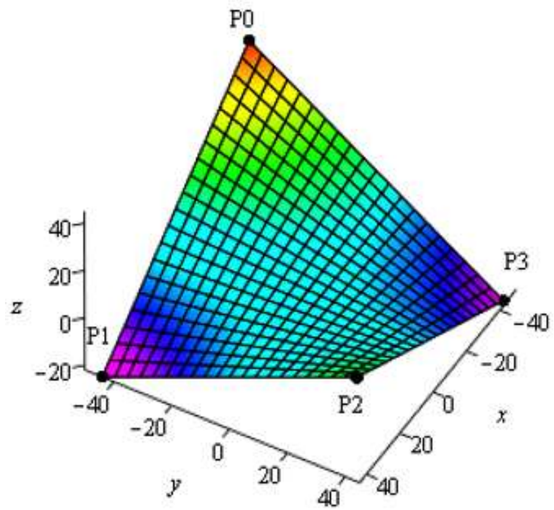
Hyperbolic paraboloid

Mathematical model

Explicit equation

$$z(x, y) = p + k(x - m)(y - n),$$

where (m, n, p) are Cartesan coordinates of vertex and k is a shape coefficient

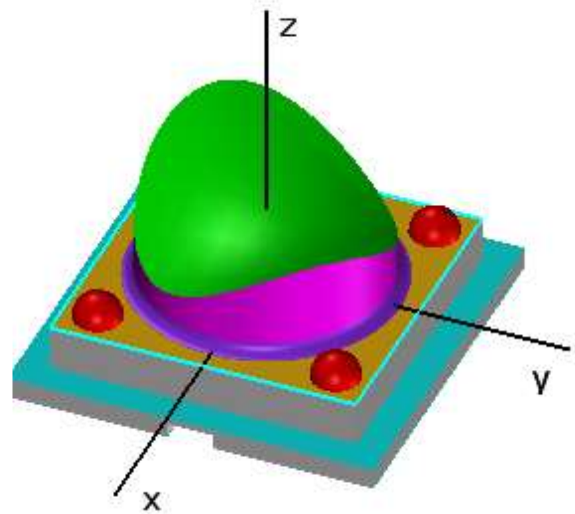


CAD model

Exact NURBS representation

$$\mathbf{S}(u, v) = \sum_{i=0}^{1} \sum_{j=0}^{1} \mathbf{P}_{i,j} N_{i,1}(u) N_{j,1}(v),$$

where $\mathbf{P}_{i,j}$ are control points,
$N_{i,1}(u)$ and $N_{j,1}(v)$ are linear B-spline basis functions



FF-MS Hyperbolic paraboloid

in procedures for ensuring reliable measurements on machine tools, demonstration and integration focused on end-user needs

- **HOW TO USE FREEFORM STANDARD?**

EURAMET

FREEFORM MEASUREMENT UNCERTAINTY EVALUATION

$$E_n = \frac{|X_R - X_L|}{\sqrt{U_R^2 + U_L^2}}, E_n \leq 1$$

X_R reference value measured on CMM

X_L measured value on a tested CNC machine

U_R reference measurement uncertainty of CMM

U_L measurement uncertainty of a tested CNC machine

U_L ... UNKNOWN VALUE

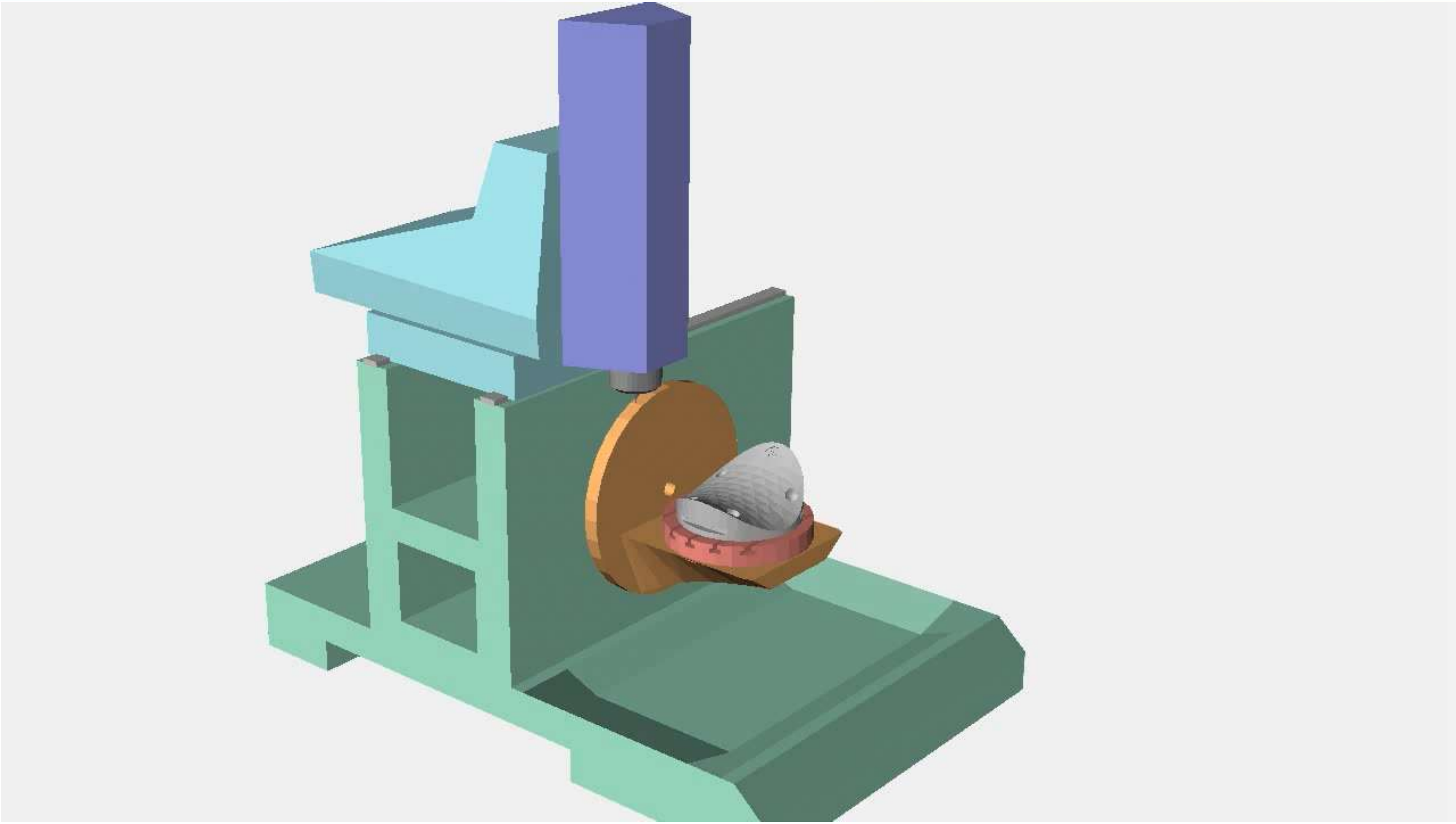
$$U_L = \pm\sqrt{\frac{(X_R - X_L)^2}{E_n^2} - U_R^2}, \qquad \frac{(X_R - X_L)^2}{E_n^2} \geq U_R^2.$$

PILOT MEASUREMENT

SIP CMM 5

PILOT LABORATORY SPECIFICATION	
Measurement system	Tactile
Max. perm. error	(0.5 + 0.8L) µm
Measurement uncertainty	1.6 µm
Maximal measurement dimensions	Length 720 mm Width 720 mm Heigth: 550 mm

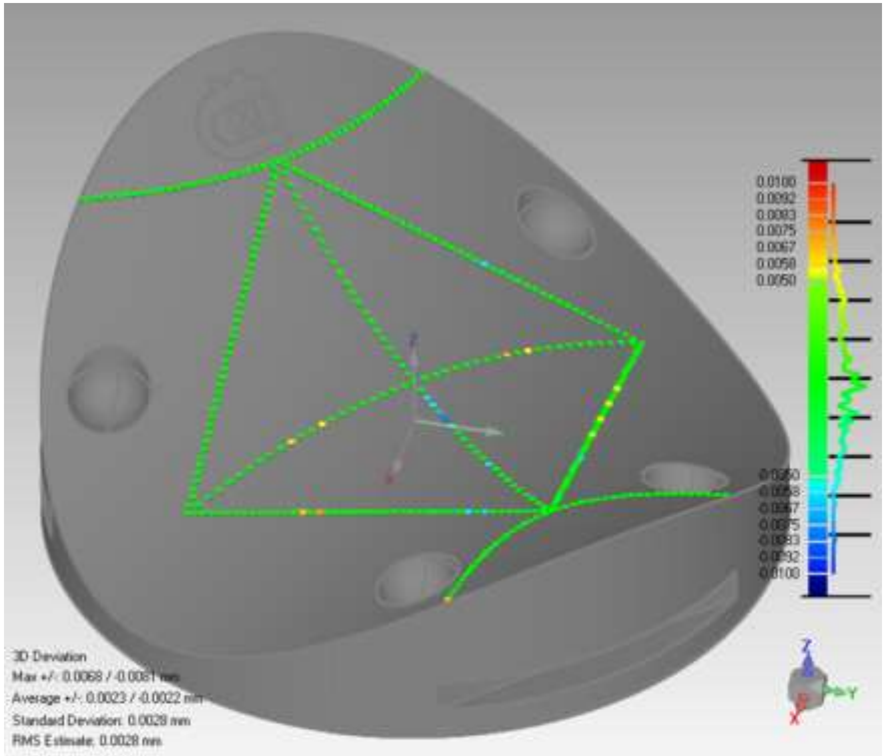
Measurement of 3D line on machine tool



Reliable measurements on machine tools

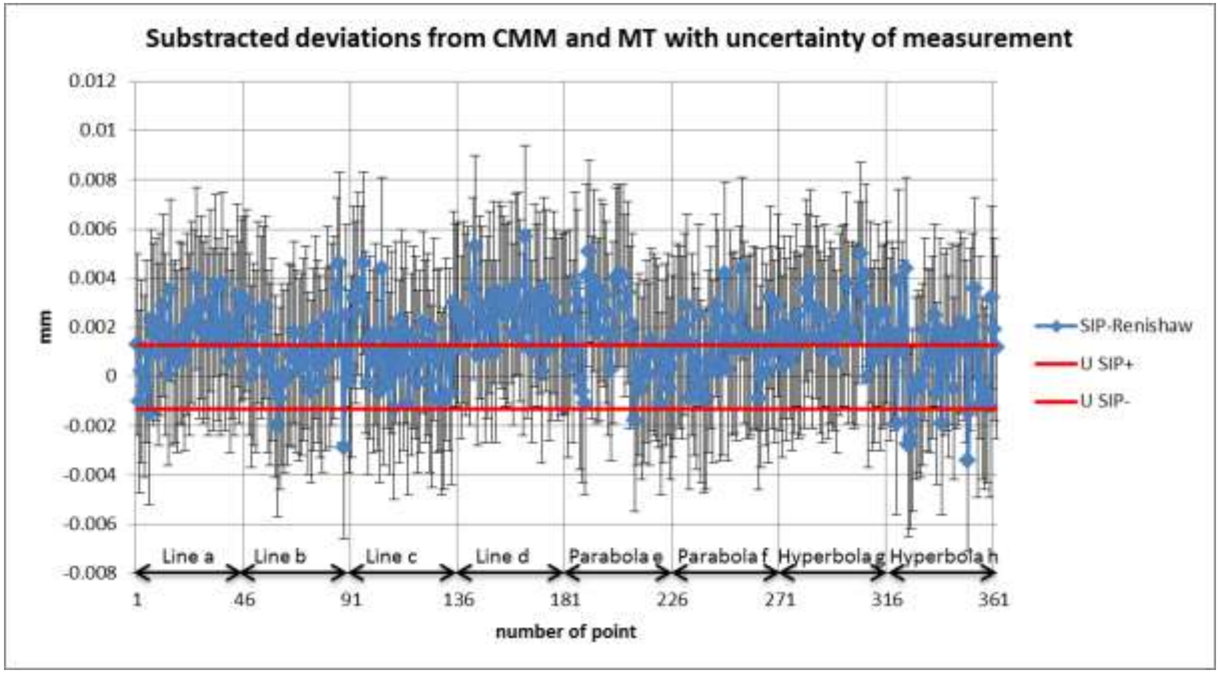
MEASUREMET LAB 1.1	
Measured standard	HP PA
Output data format	TXT Points along curves and lines on freeform surface
Evaluation SW	Geomagic
Comparison method	Bestfit alignment against the CAD model
Measurand definition	Deviation between the actual and nominal data, form error
Results representation	Colour map of deviations
Form error	[-8.1, 6.8] µm
Average deviation (one-sigma limits)	2.3, -2.2 µm
Standard deviation	2.8 µm

HP PA



En criterion in in-process measurement

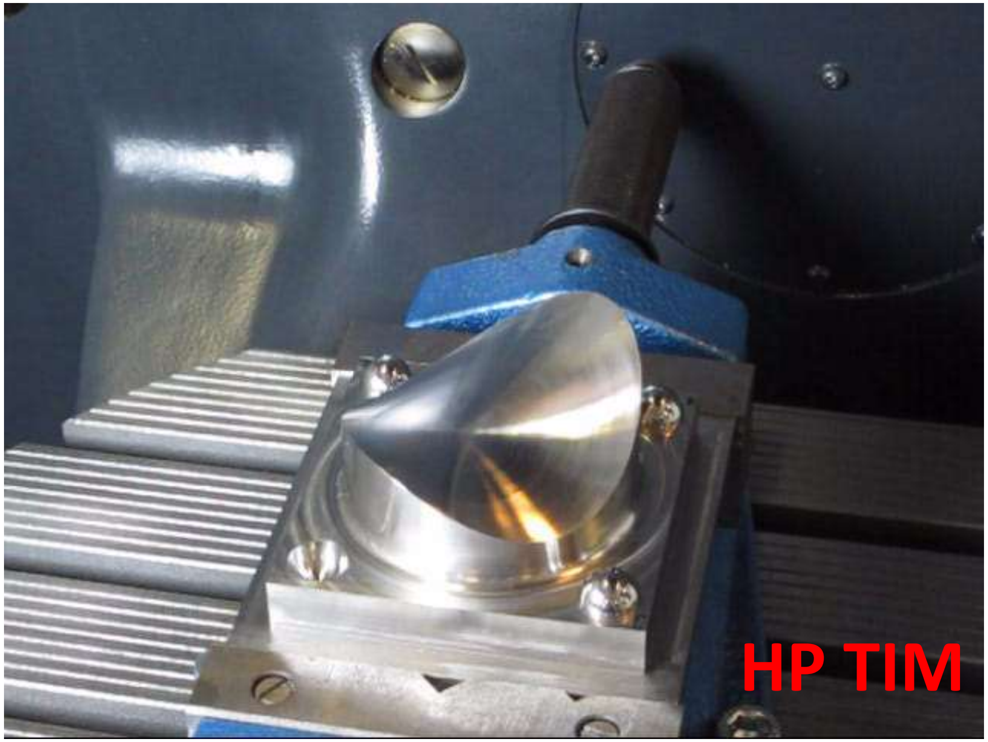
MEASUREMET LAB 1.1	
Measurand X_L	Deviation of each measured point obtained by Measurement 1.1 from reference CAD model
Limits of evaluation	Two-sigma limits
U_R	± 1.6 μm



HP PA

$$U_L = \pm 3.7\ \mu m$$

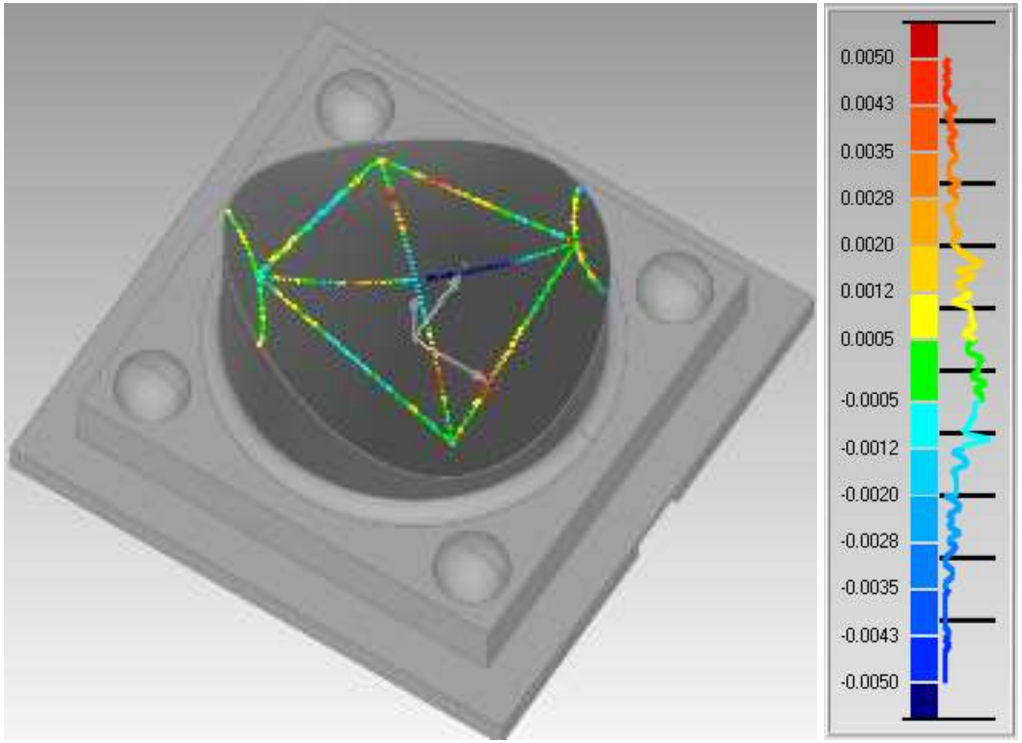
Coordinate system determination



Curves on freeform surface measurement

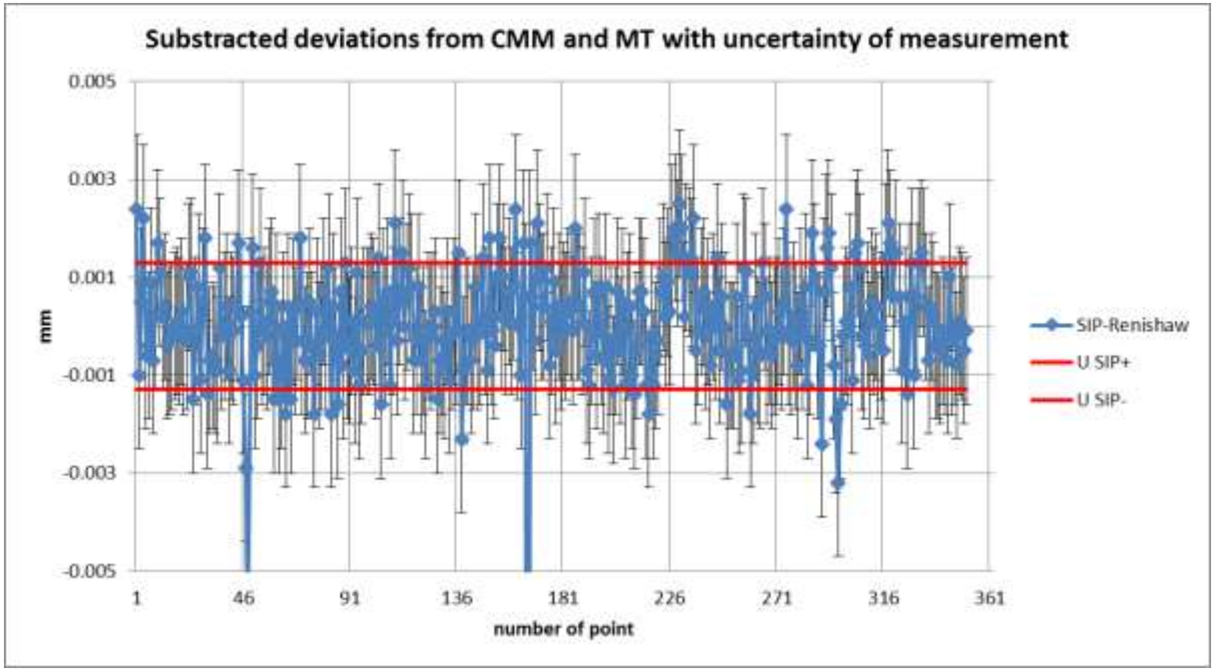
MEASUREMET LAB 1.2	
Measured standard	HP TIM
Output data format	TXT Points along curves and lines on freeform surface
Evaluation SW	Geomagic
Comparison method	Bestfit alignment against the CAD model
Measurand definition	Deviation between the actual and nominal data, form error
Results representation	Colour map of deviations
Form error	[-24.7, 6.6] µm
Average deviation (one-sigma limits)	1.6, -1.8
Standard deviation	2.8 µm

HP TIM



En criterion in in-process measurement

MEASUREMET LAB 2.2	
Measurand X_L	Deviation of each measured point obtained by Measurement 1.2 from reference CAD model
Limits of evaluation	Two-sigma limits
U_R	± 1.6 µm



HP TIM

$$U_L = \pm 1.5\ \mu m$$

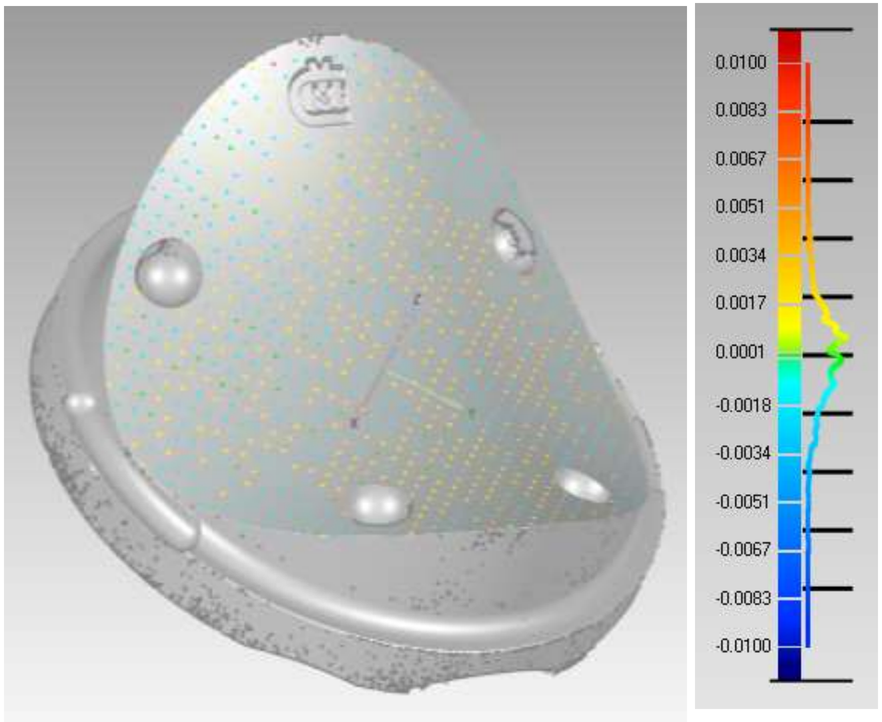
LABORATORY 2

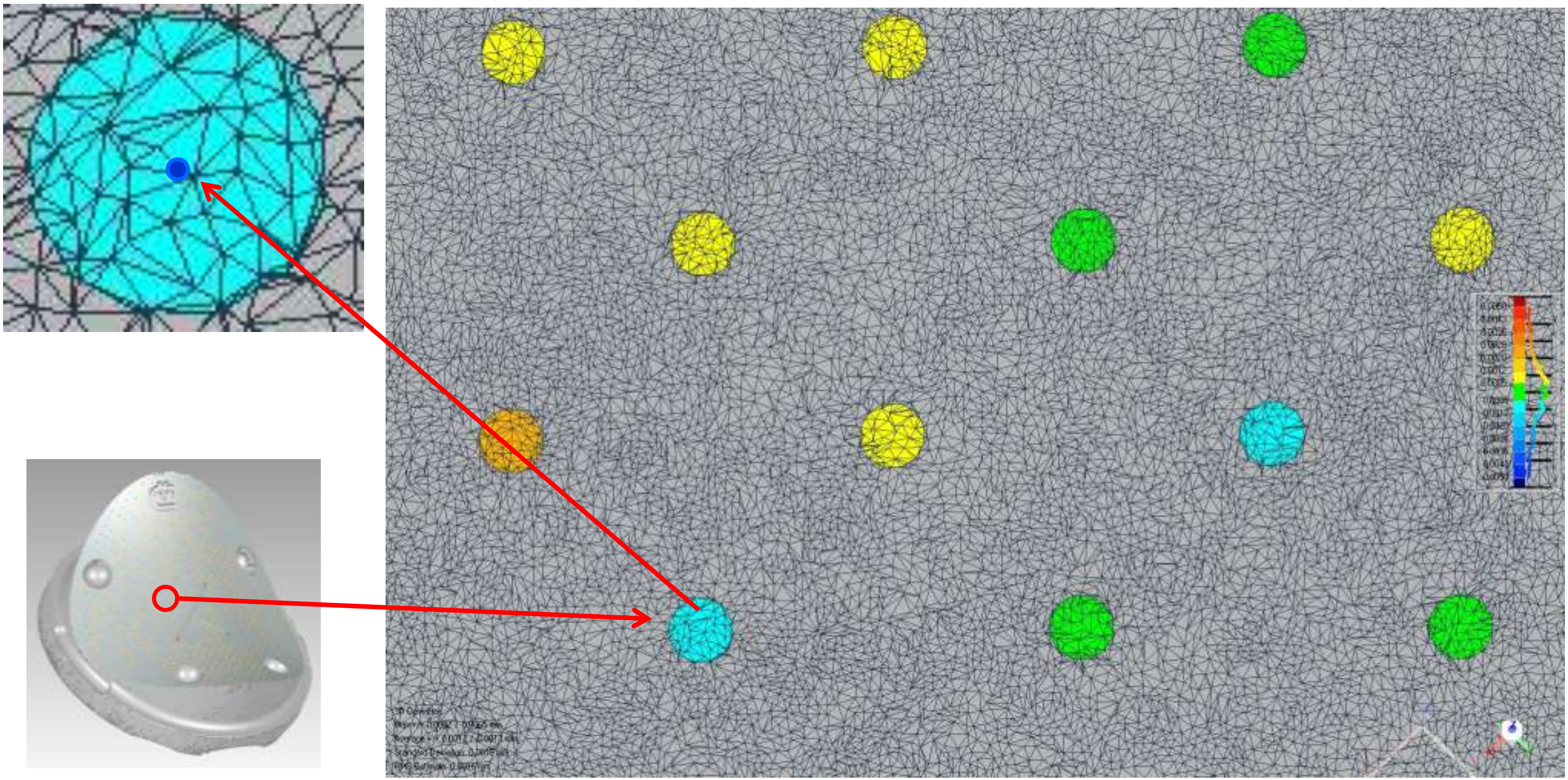
ATOS Triple Scan

LABORATORY 2 SPECIFICATION	
Measurement system	3D optical
Maximal measurement dimensions	170 x 130 - 810 x 610 mm^2

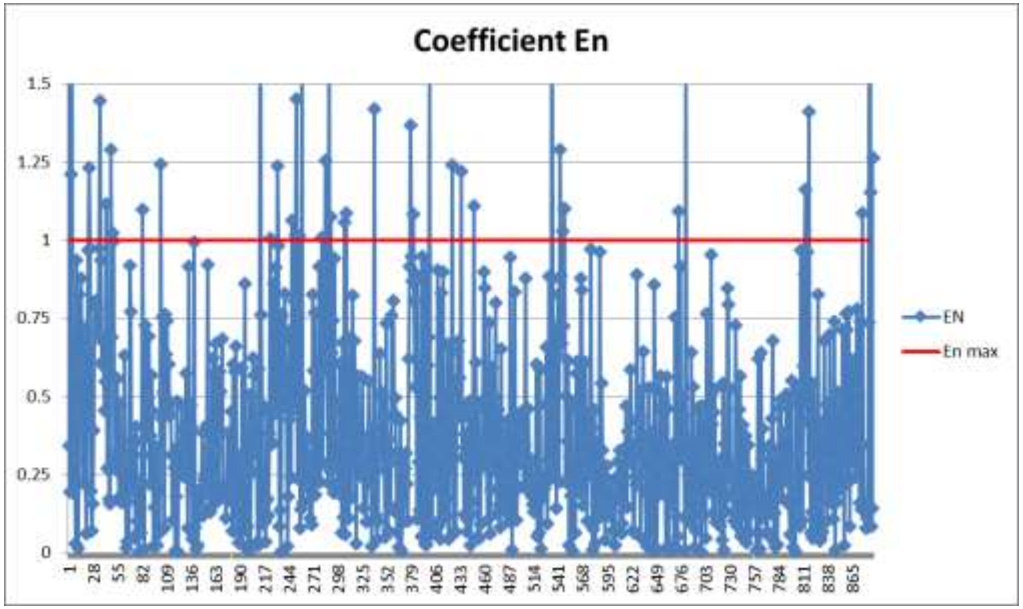
MEASUREMET LAB 2	
Measured standard	HP PA
Output data format	STL – 3D point cloud
Evaluation SW	Geomagic
Comparison method	Bestfit alignment against the pilot data
Measurand definition	Deviation between the actual and pilot data
Results representation	Colour map of deviations
Form error	[-6.5, 8.4] µm
Average deviation (one-sigma limits)	1.2 µm, -1.3 µm
Standard deviation	1.6 µm

HP PA





MEASUREMET LAB 2	
Measurand X_L	Deviation of point corresponding to SIP point obtained by Measurement 2 from reference CAD model
Limits of evaluation	Two-sigma limits
U_R	± 1.6 µm



HP PA

$$U_L = \pm 2.8\ \mu m$$

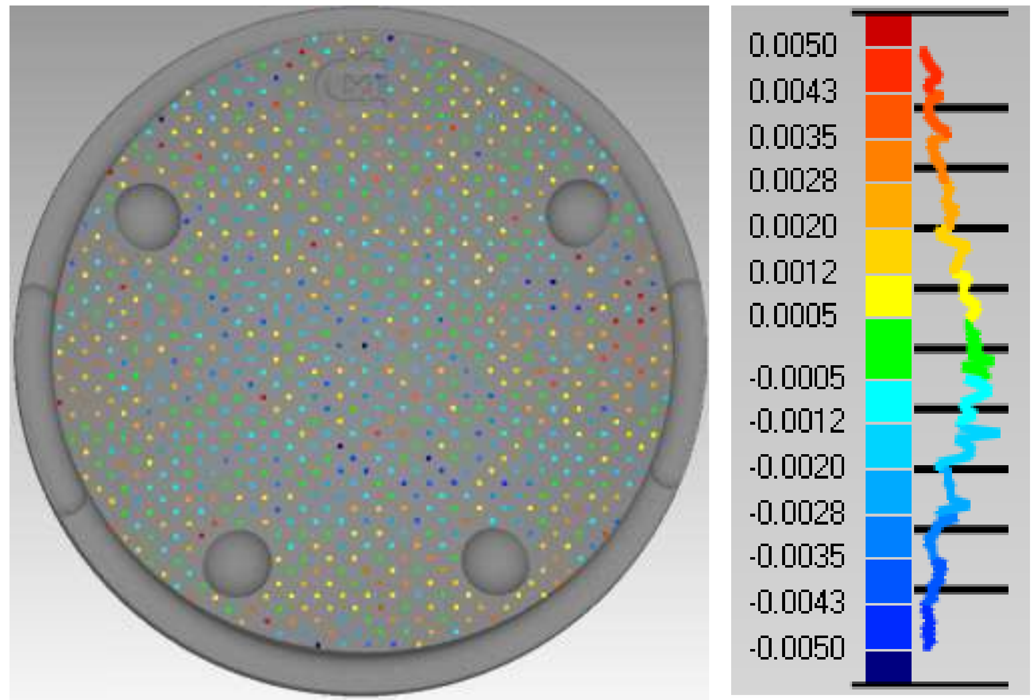
LABORATORY 3

WERTH TOMOSCOPE HV 500

LABORATORY 3 SPECIFICATION	
Measurement system	Multisensor + tactile scanning probe
Max. perm. error	(4.5 + L/75) µm
Maximum X-ray voltage	300 kV
Maximum X-ray performance	300 W
Resolution	(2048 × 2048) pix.
Sensor area	(400 × 400) mm
Maximal measurement dimensions	Length 710 mm Diameter 500 mm
Maximal workpiece weight	75 kg

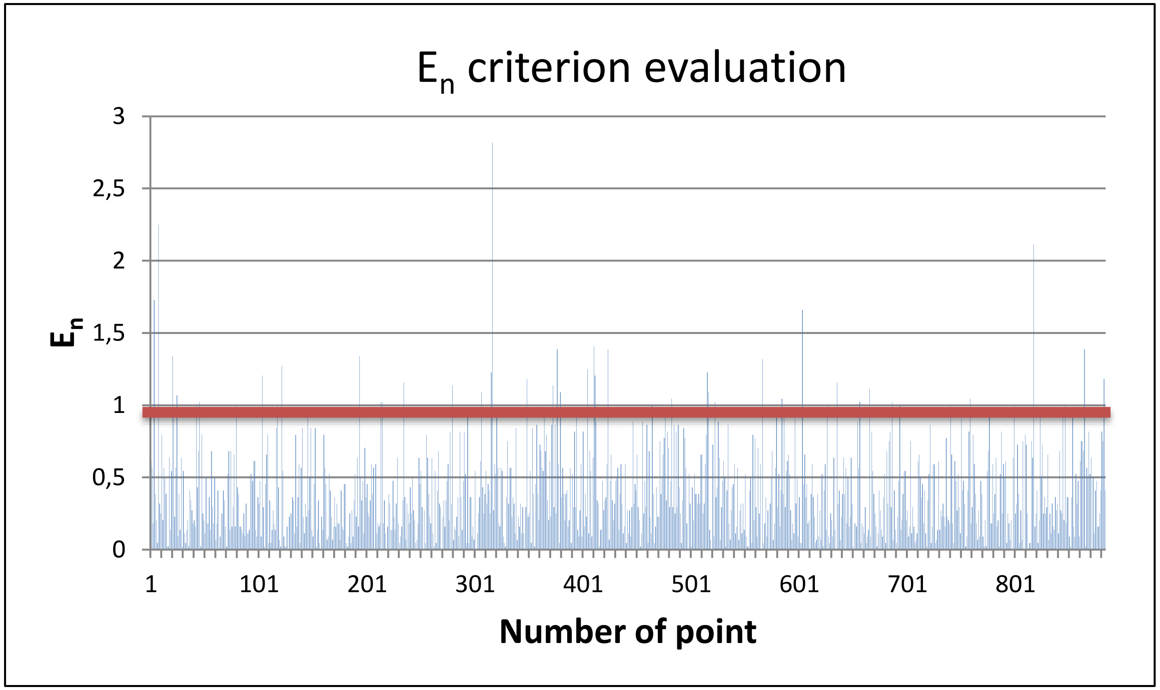
MEASUREMET LAB 3	
Measured standard	HP PA
Output data format	STL – 3D point cloud
Evaluation SW	Geomagic
Comparison method	Bestfit alignment against the pilot data
Measurand definition	Deviation between the actual and pilot data
Results representation	Colour map of deviations
Form error	[-7.6, 12.4] µm
Average deviation (one-sigma limits)	1.8 µm, -1.6 µm
Standard deviation	2.2 µm

HP PA



En criterion in in-process measurement

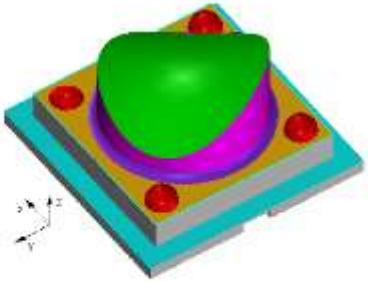
MEASUREMET LAB 3	
Measurand X_L	Deviation of each calibrated point obtained by pilot tactile measurement from 3D point cloud obtained by Measurement 3
Limits of evaluation	Two-sigma limits
U_R	± 1.6 µm



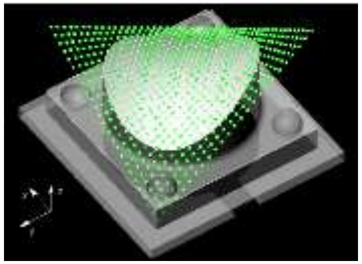
HP PA

$$U_L = \pm 4.1\ \mu m$$

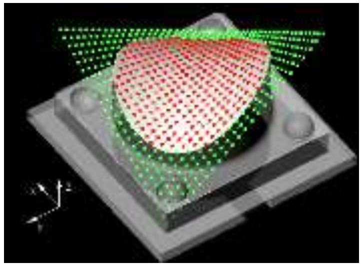
Original mathematical CAD model



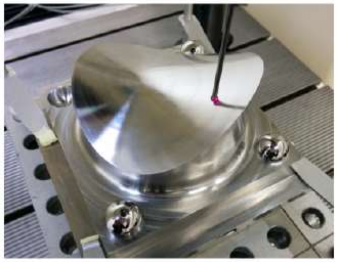
Original control mesh refinement



Input data for primary measurement definition



Primary measurement with respect to the original CAD



1st stage calibrated CAD model

Bicubic B-spline surface given by finer control mesh where the theoretical control points are replaced by measured points

Control mesh of 1st stage calibrated CAD model refinement

Input data for secondary measurement definition

Secondary measurement with respect to the 1st stage calibrated CAD model

2nd stage calibrated CAD model

Bilinear B-spline surface given by finer control mesh of 1st stage calibrated CAD model where the theoretical control points are replaced by measured points

2nd stage calibrated CAD model verification

Input 1: set of 225 points independent on control mesh

Reference CAD: 2nd stage calibrated CAD model

Form error: [-1.2, 1.4] µm

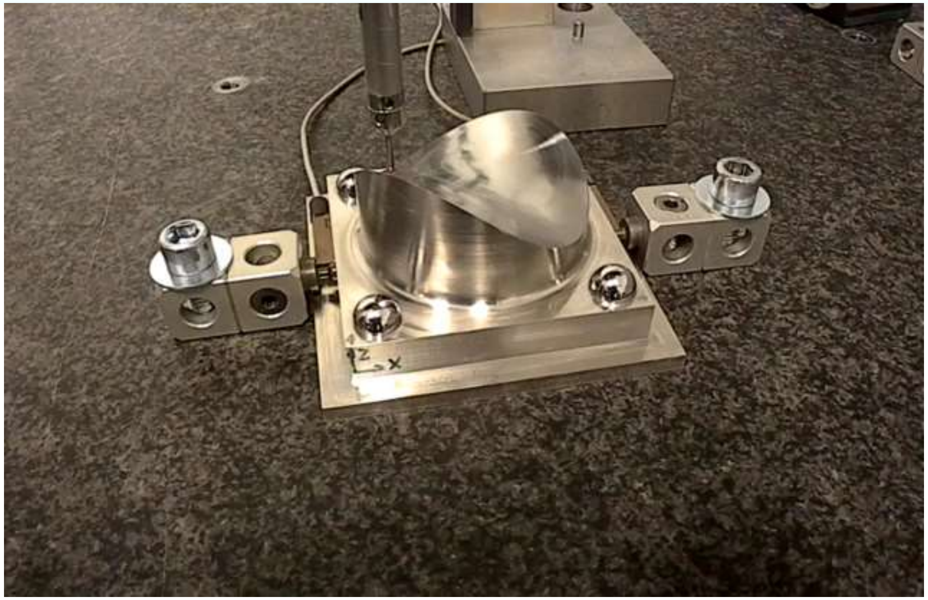
Input 2: set of 4644 points independent on control mesh

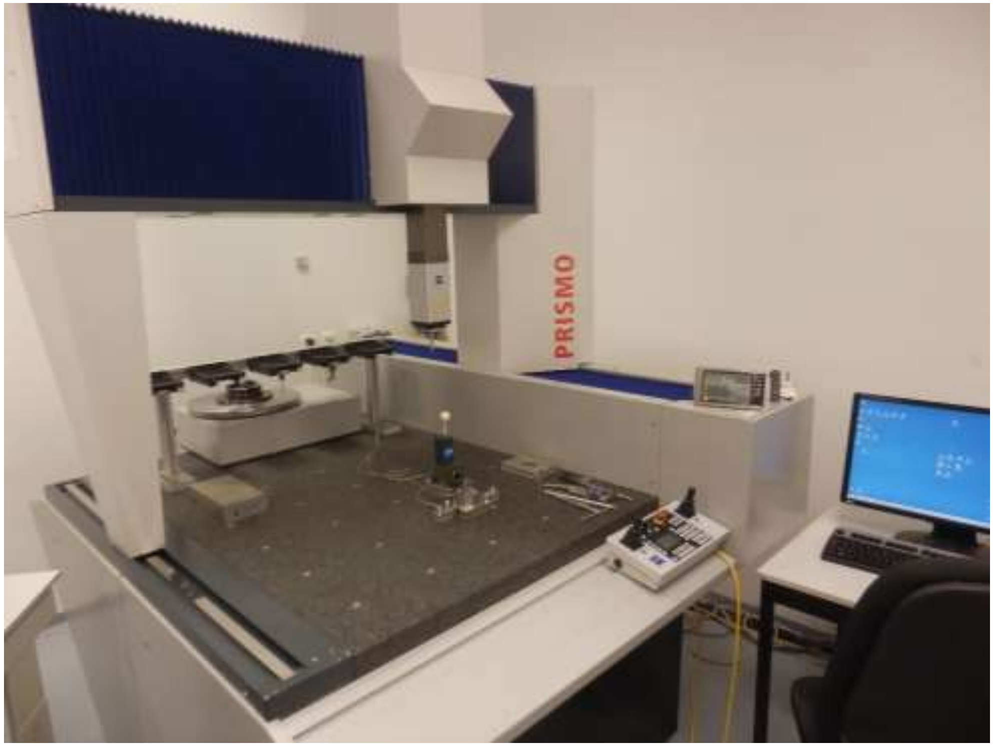
Reference CAD: 2nd stage calibrated CAD model

Form error: [-1.5, 1.4] µm

LABORATORY 5

ZEISS PRISMO

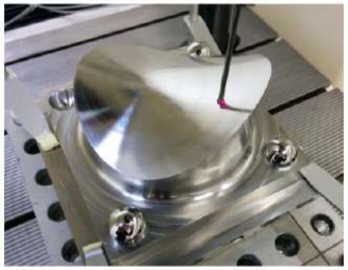


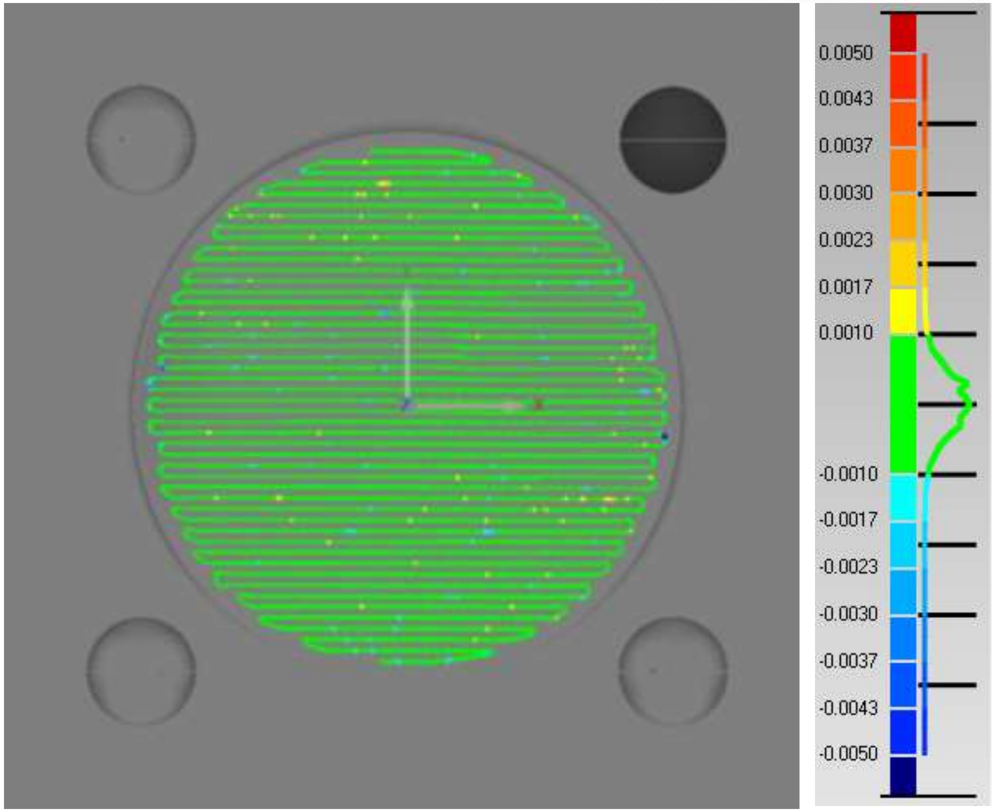


LABORATORY 5 SPECIFICATION	
Measurement system	Active scanning probe VAST
Max. perm. error	(1.0+L/330) µm
Maximal measurement dimensions	Length 1200 mm Width 850 mm Height 700 mm

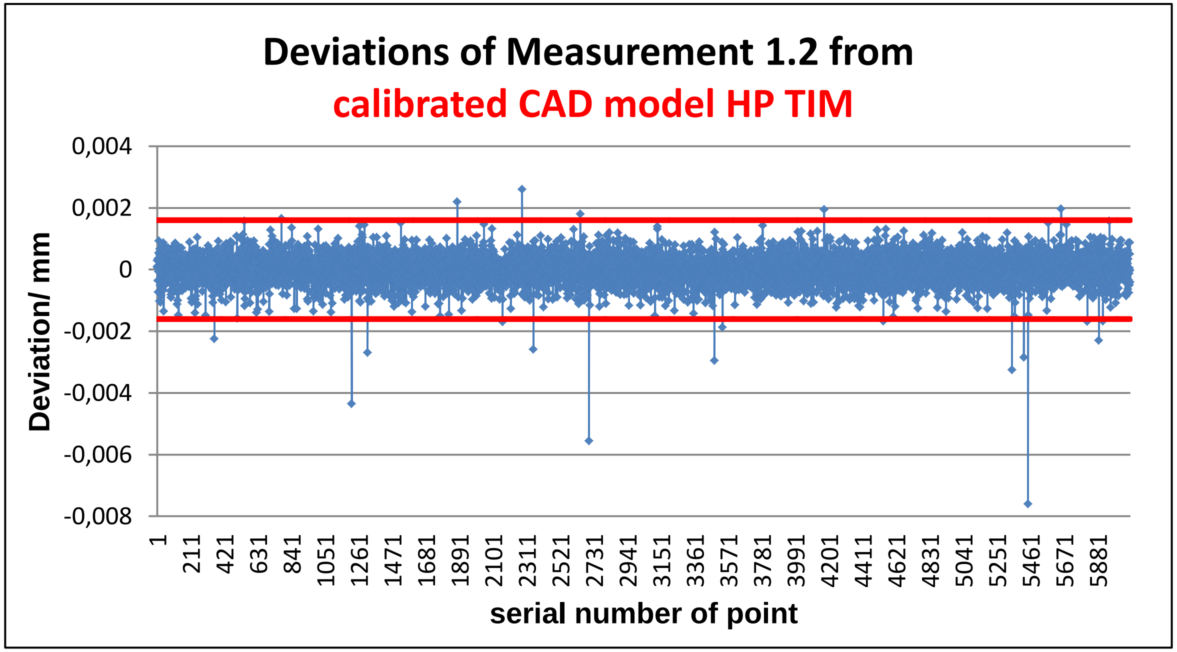
MEASUREMET LAB 5	
Measured standard	HP TIM
Output data format	TXT Points obtained by scanning probe
Evaluation SW	Geomagic
Comparison method	Bestfit alignment against the **calibrated CAD model**
Measurand definition	Deviation between the actual and nominal data, form error
Results representation	Colour map of deviations
Form error	[-7.6, 2.6] µm
Average deviation (one-sigma limits)	± 0.4 µm
Standard deviation	0.5 µm

HP TIM



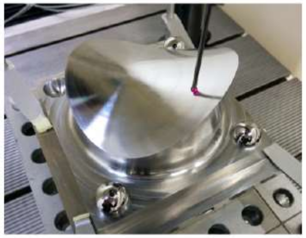


MEASUREMET LAB 5	
Measurand X_L	Deviation of each measured point obtained by Measurement 5 from reference **calibrated CAD model**
Limits of evaluation	Two-sigma limits
U_R	± 1.6 µm



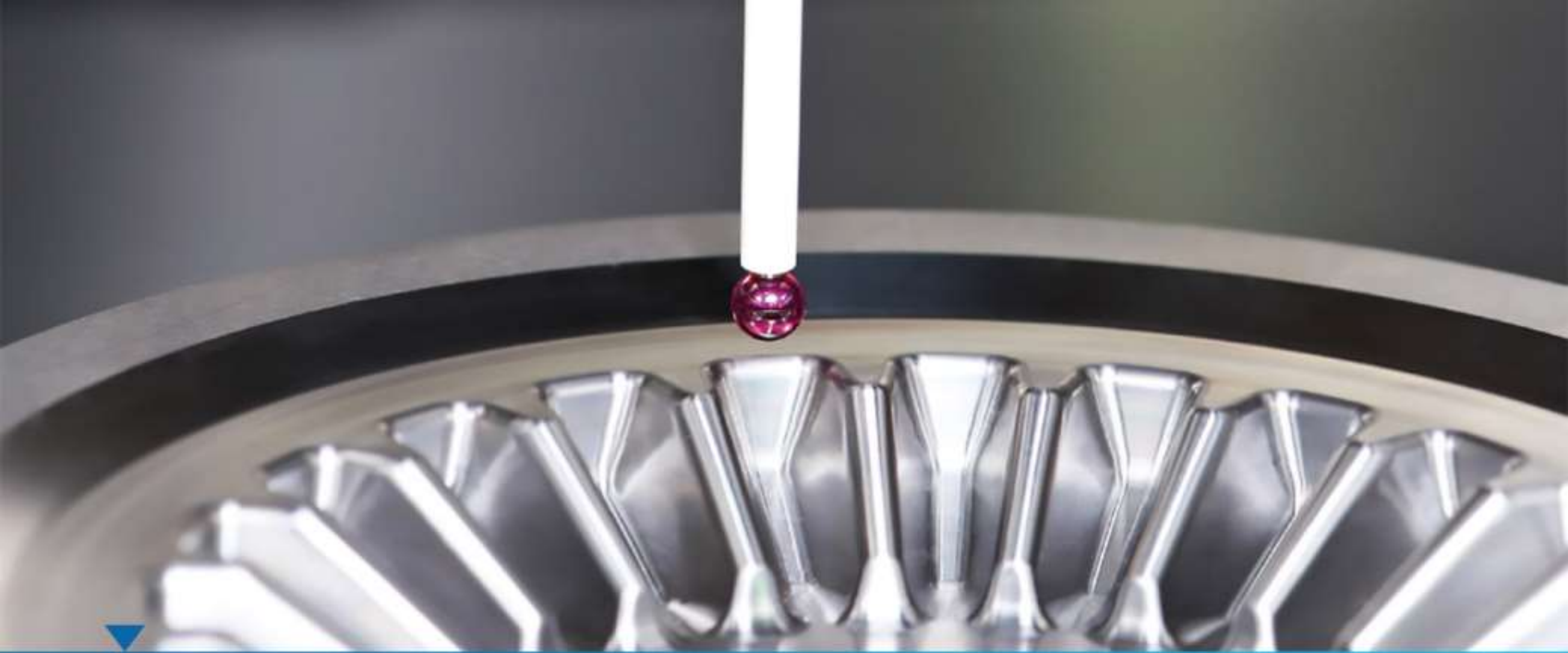
HP TIM

$$U_L = \pm 1.0\ \mu m$$



INTERCOMPARISON

	Meas. technology	Measuring machine	Measurand	Measuremen uncertainty
PILOT	Tactile on CMM	SIP	Deviation of surface point from reference model	$U_L = \pm 1.6\ \mu m$
LAB 1	Tactile on CNC	Resnishaw	Deviations of measured points from CAD	$U_L = \pm 3.7\ \mu m$ $U_L = \pm 1.5\ \mu m$
LAB 2	Optical 3D scanner	ATOS Triple Scan	Deviation of pilot data from STL	$U_L = \pm 2.8\ \mu m$
LAB 3	Laser scanner	FARO Arm	Deviation of pilot data from STL	$U_L = \pm 40\ \mu m$
LAB 4	Computer tomography	Werth CT	Deviation of pilot data from STL	$U_L = \pm 4.1\ \mu m$
LAB 5	Tactile active scanning probe	ZEISS	Deviations of measured points from calibrated CAD	$U_L = \pm 1.0\ \mu m$



THANKS FOR YOUR ATTENTION

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