ISM3D

Overview over the different measurement methods for geometry error correction for measuring machines and machine tools

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NACMA

NORTH AMERICAN COORDINATE METROLOGY ASSOCIATION
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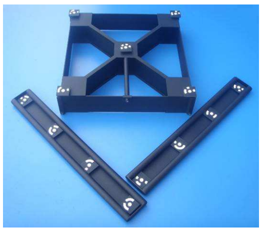
04 - 06 AUGUST 2010 MINNEAPOLIS, MINNESOTA, USA

ISM3D

- **ISM3D:**
  Measurement service and training provider in the north of Spain
  … several high accuracy CMMs, partly self retrofitted (I++) and compensated (with own artefacts)

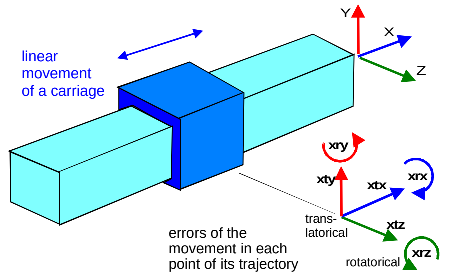


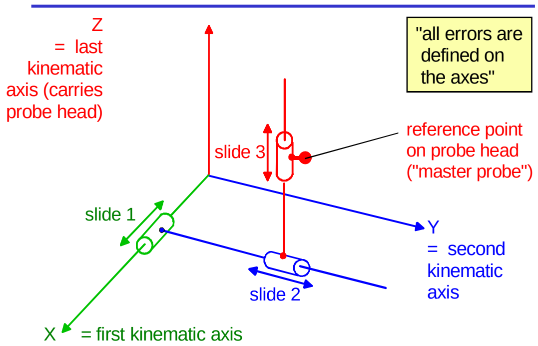
- **Trapet Precision:**
  Metrology engineering, artifact development and manufacturing, correction software tools (compensation module for integration), uncertainty evaluation tools (Virtual CMM for integration)

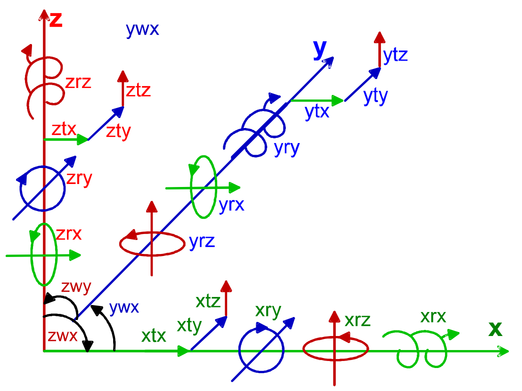
Contents

- Errors to deal with
  - linear axes
  - rotary axes
  - rigid body model errors
  - non-rigid-body model errors
- Applying corrections
  (“standard formats”)
- Measurement devices and methods
  - direct selective methods
    X Y X (displacement or position)
    angle (displacement or position)
  - indirect analytic methods
    X Y Z (displacement or position)
- Verifying corrections and maintaining corrections valid
- Conclusions

Numerical correction of geometry errors “Rigid Body Error Model”







Parametric Errors of a Three Cartesian Axis Machine

Numerical correction of geometry errors
Gantry specific errors, rotary axes

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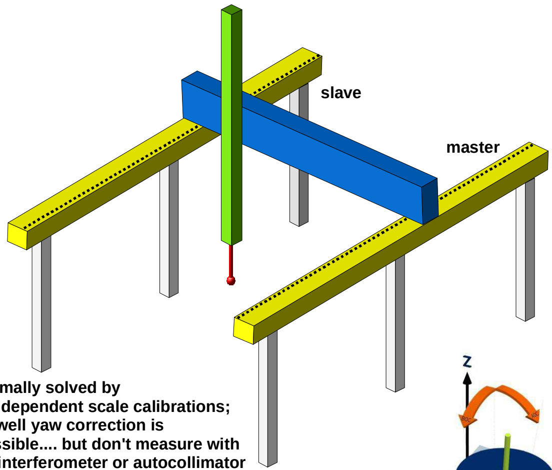
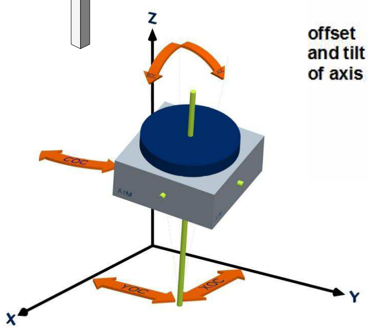
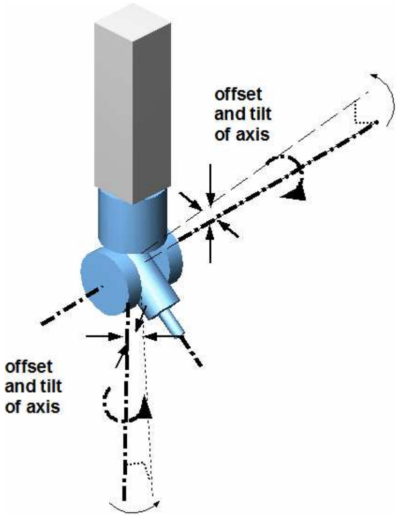


normally solved by
2 independent scale calibrations;
as well yaw correction is
possible.... but don't measure with
tilt interferometer or autocollimator





Numerical correction of geometry errors
“Non-Rigid-Body Errors”

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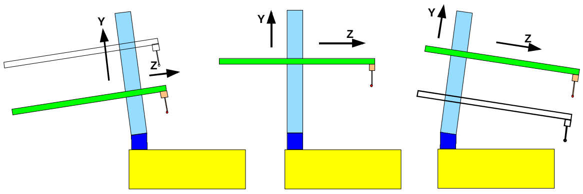
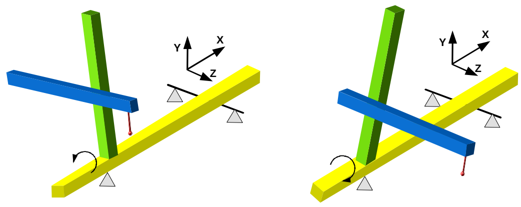
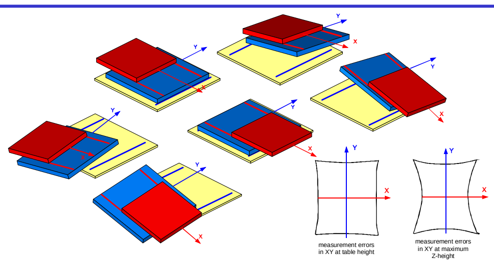
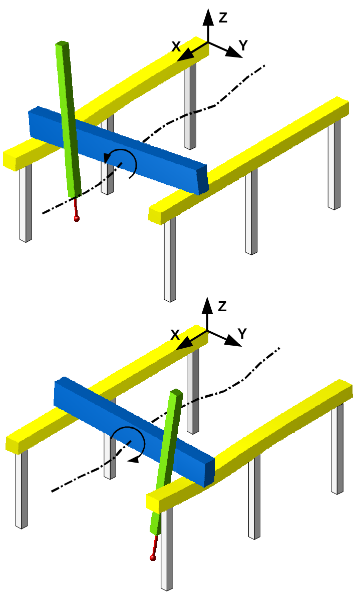
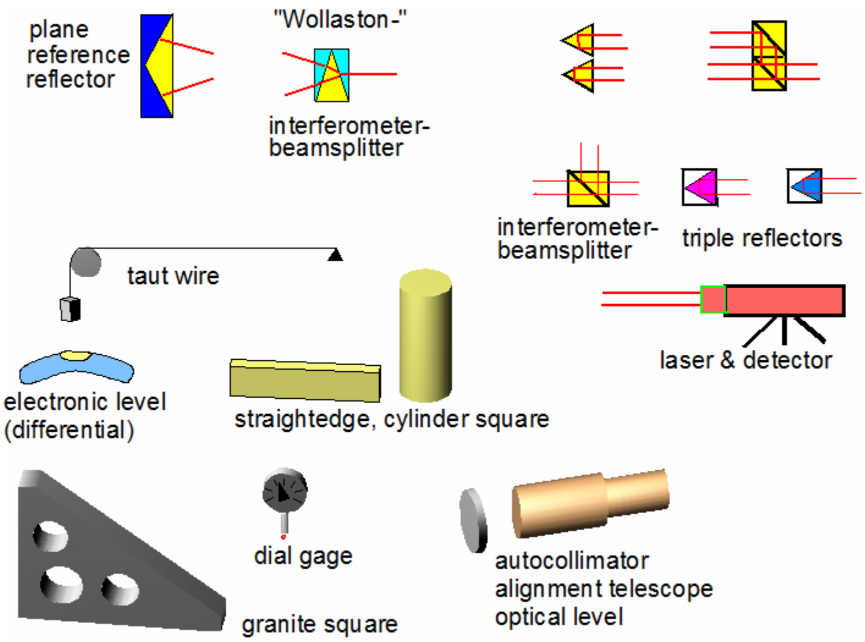




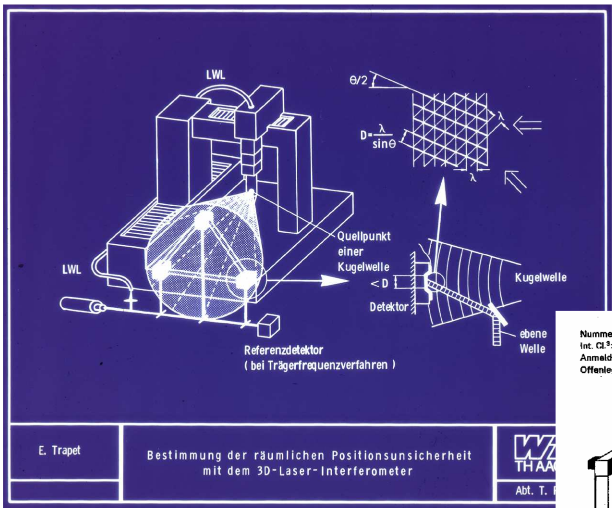


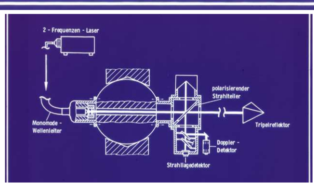


Classical measurement devices used for machine alignment and error parameter measurement



Correction of geometry errors: Origins of 3D interferometric measurements





United States Patent [19]

Greenleaf et al.

[54] SELF CALIBRATING CONTOUR MEASURING SYSTEM USING FRINGE COUNTING INTERFEROMETERS

[75] Inventors: Allen H. Greenleaf; John T. Watson, both of Lexington, Mass.

[73] Assignee: Itek Corporation, Lexington, Mass.

[21] Appl. No.: 282,552

[22] Filed: Jul. 13, 1981

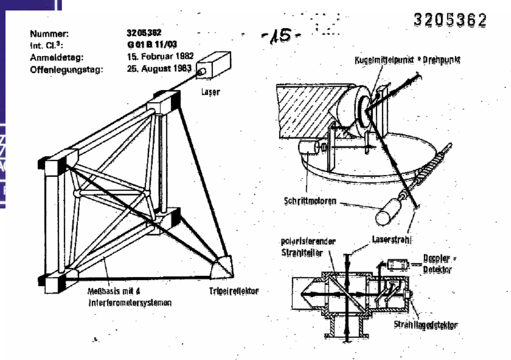
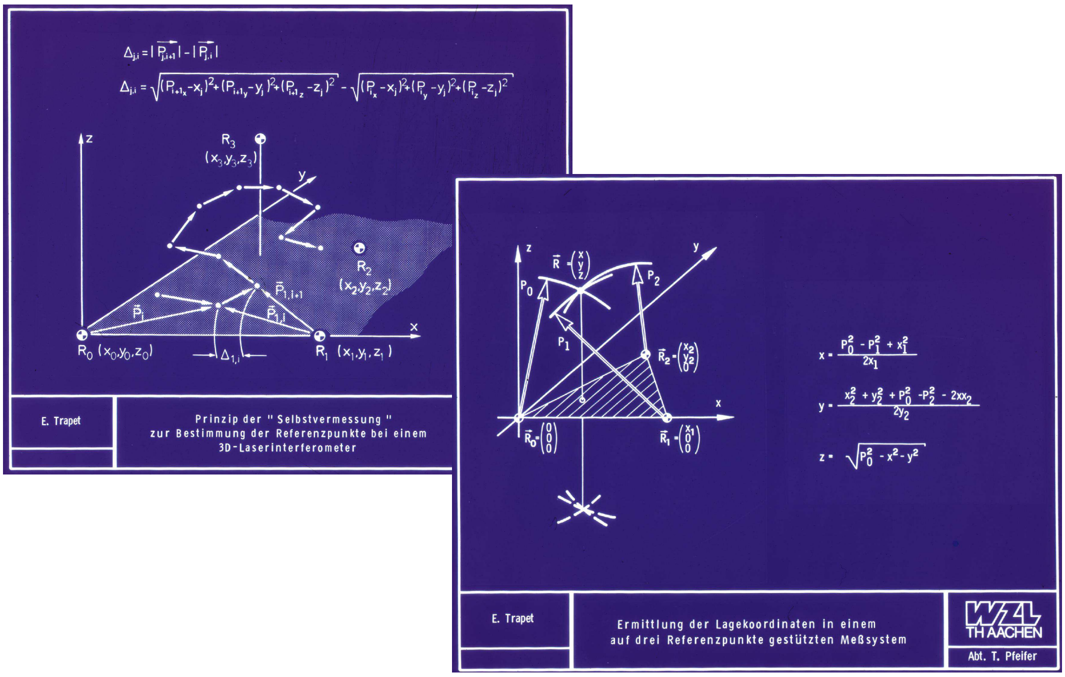
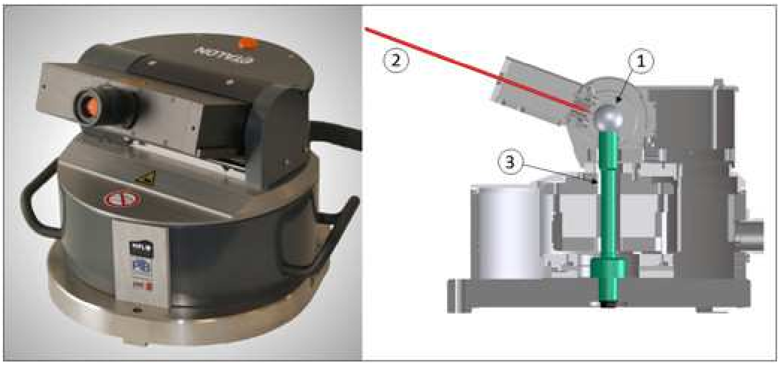


Bild 1 3D-Laserinterferometersystem

Correction of geometry errors: Origins of 3D interferometric measurements



The Laser Tracer



Laser Tracer hardware

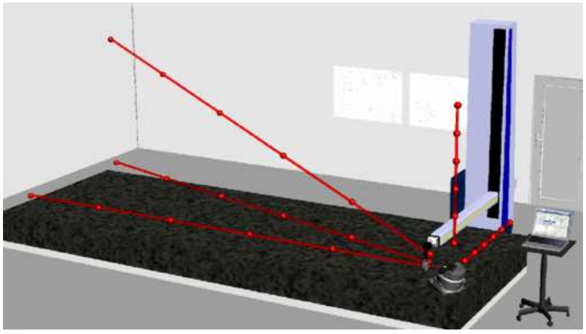
on the fly measurement

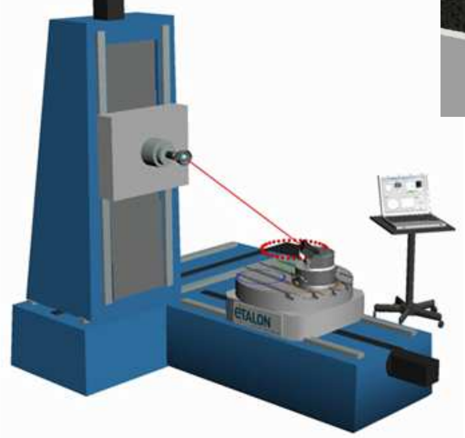
Videos!

Courtesy: ETALON

Special features of the Laser Tracer concept

Machine performance verification according to ISO 230-2 ff: axial and space-diagonal displacement measurements



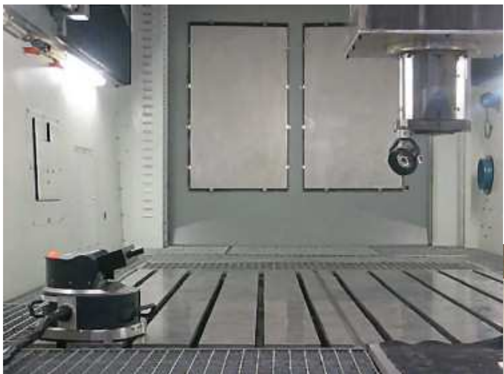


Courtesy: ETALON

Rotary table calibration: axis direction and position

Videos!

Laser Tracer on machine tools



Courtesy: ETALON

Errors before compensation and re-measured with compensation activ (all with Laser Tracer)

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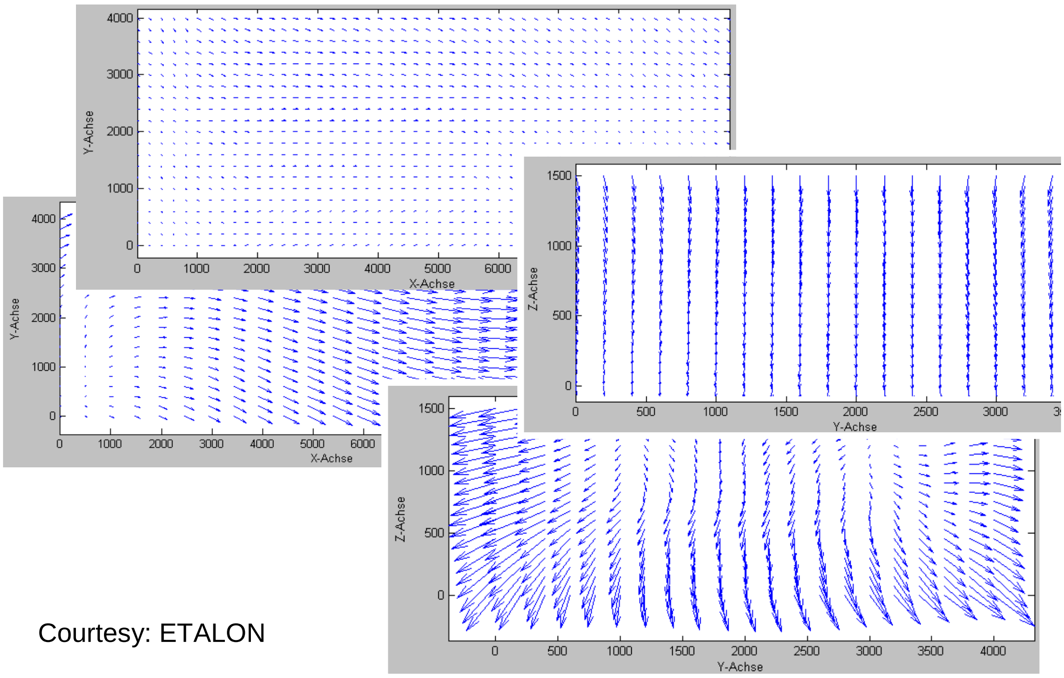
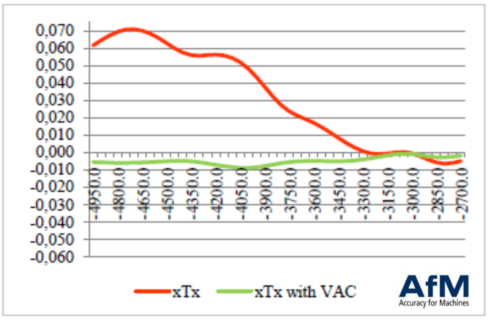
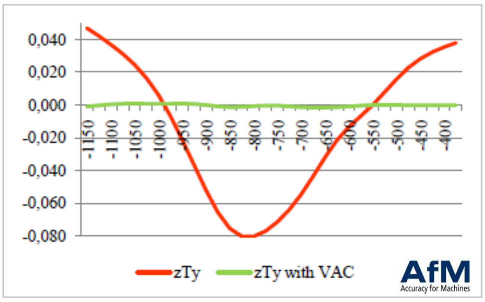


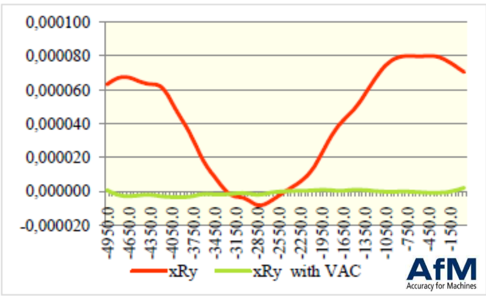
Courtesy: ETALON

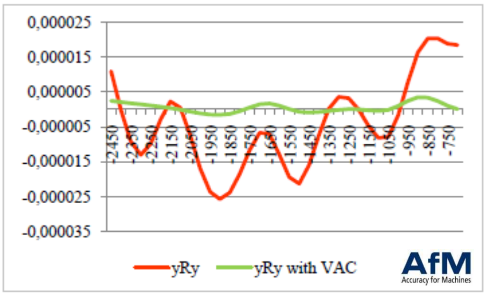
Errors before compensation and re-measured with compensation active (all with Laser Tracer)

ISM3D

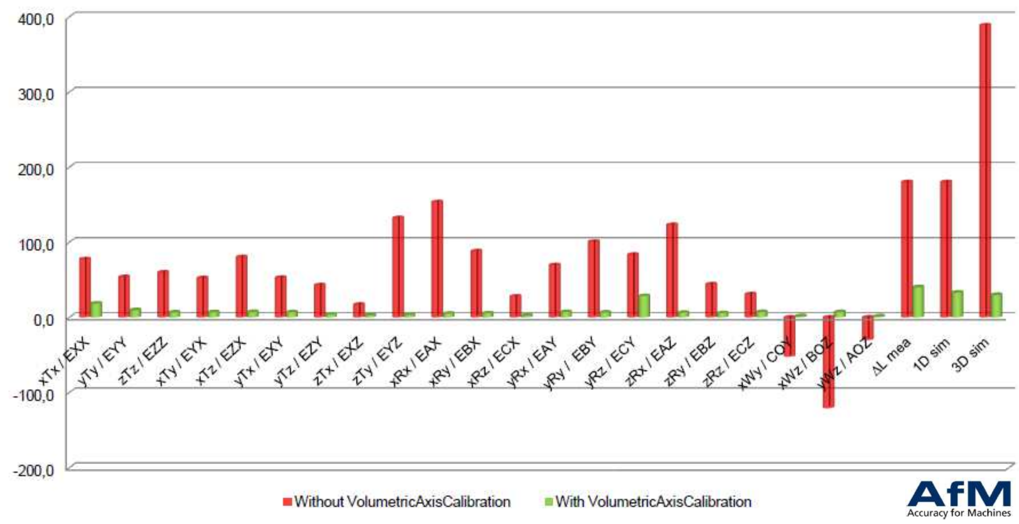








All errors before compensation and re-measured with compensation active, courtesy: AFM-Tec

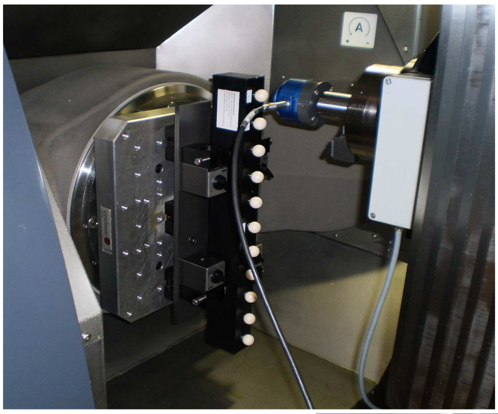


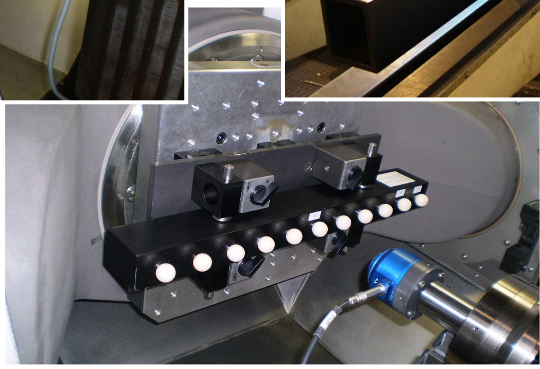
The Laser Tracer MT

Videos!

Courtesy: ETALON

3D ball beams and self-centring probe





3 errors “at once”,
6 in combination with
several beam positions

10-30 minutes per axis

Uncertainty of probe:
< 0.0006 mm

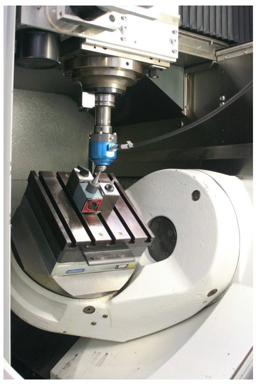
from project
“MT-Check”

Courtesy:
IBS-PE

Measurement of rotary axes with self-centring probe

Problem: the exact location & squareness of a rotary axis is not well known at the micrometre level of 5 axis machine tool.

Swivel head machine (large machines)

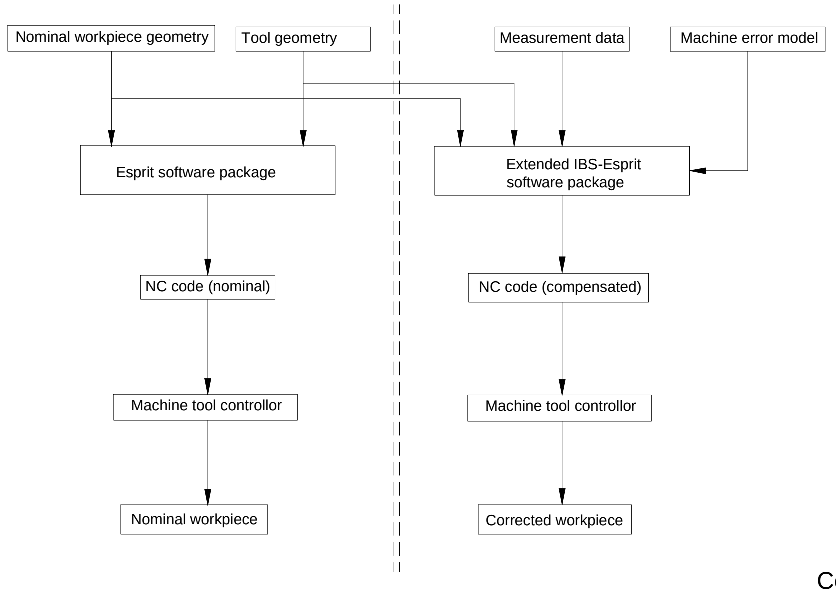


Trunnion table machine (large and small exist)

Courtesy:
IBS-PE

Video!

Pre-correction of NC-Programs

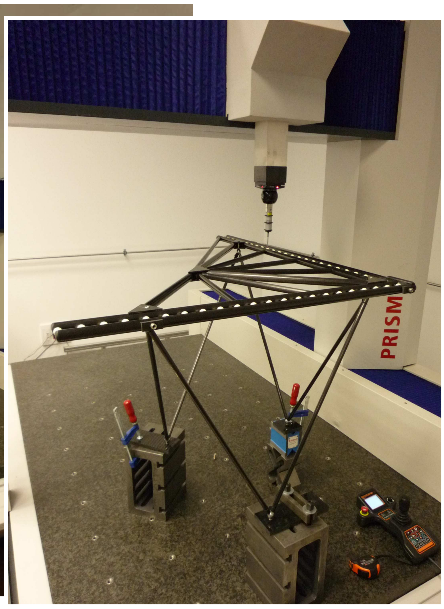


Main flowchart of compensation software package

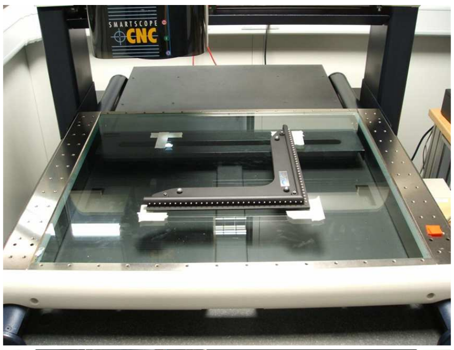
Courtesy:
IBS-PE

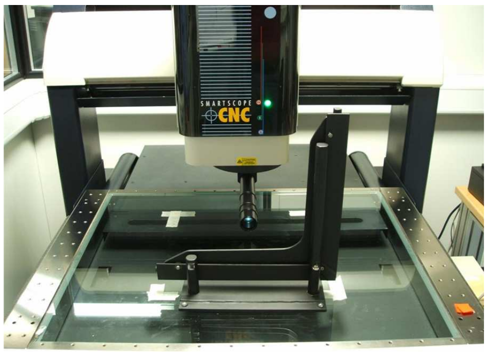
Ball beam for full error correction, tactile meaurement in typically 8 hours

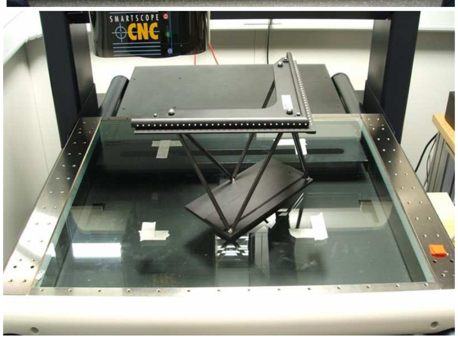
Ball plate for full error correction, tactile measurement in typically 8 hours

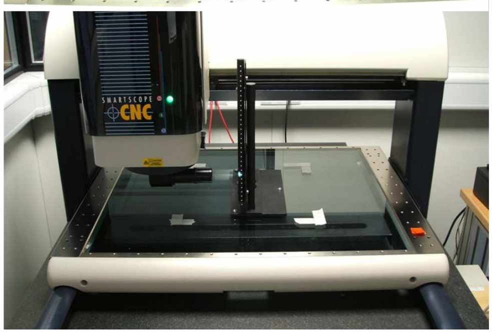


Ball plate for full error correction, optical measurement in typically 2-3 hours









Ball plate for full error correction, output of so called *.exc format, directly read by correction module

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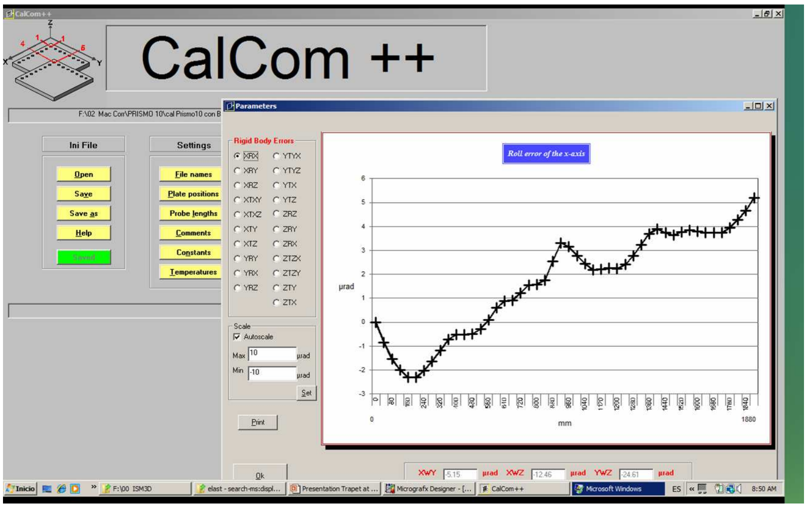


```
...
...
[ZRZ]
U_LINEAR = 0.000000000
GRIDPOINTS = {
30.0 0.000000000
70.0 0.000004209
110.0 0.000006425
150.0 0.000009621
190.0 0.000013323
230.0 0.000014222
270.0 0.000012181
310.0 0.000009768
350.0 0.000009011
390.0 0.000009572
430.0 0.000009423
470.0 0.000008328
510.0 0.000007402
550.0 0.000006916
590.0 0.000006767
630.0 0.000006787
670.0 0.000006841
710.0 0.000006692
750.0 0.000006847
790.0 0.000007610
830.0 0.000008677
870.0 0.000010488  }

[XWY]
U_CONSTANT = 0.0000000
VALUE = -0.000005145

[XWZ]
U_CONSTANT = 0.0000000
VALUE = -0.000012459

[YWZ]
U_CONSTANT = 0.0000000
VALUE = -0.000024607

[XRXZ]
U_CONSTANT = 0.0000000
VALUE = _._______

[ALFAX]
U_CONSTANT = 0.0000000
VALUE = 0.000000000

[ALFAY]
U_CONSTANT = 0.0000000
VALUE = 0.000000000

[ALFAZ]
U_CONSTANT = 0.0000000
VALUE = 0.000000000

[TMATRIX]
U_CONSTANT = 0.0000000
VALUE =
1 0 0
0 1 0
0 0 1
```

Ball beam method with optical sensor for machine tools, using 2D-ball-beam

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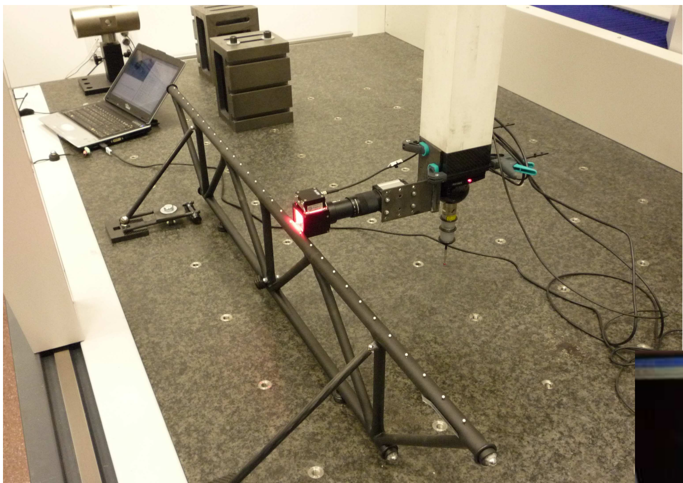
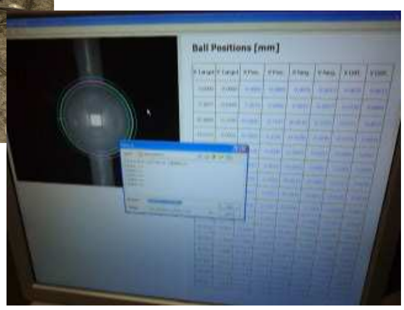


this is still a prototype sensor

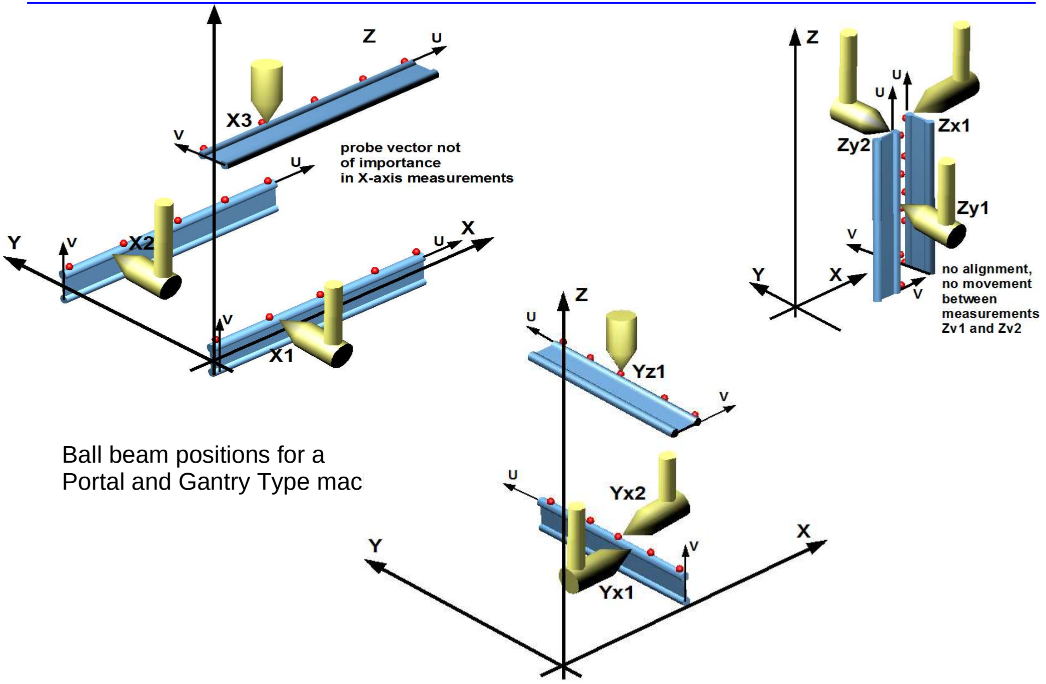
Video!



Measurement in 7 positions (full) plus 4 (á 3balls)

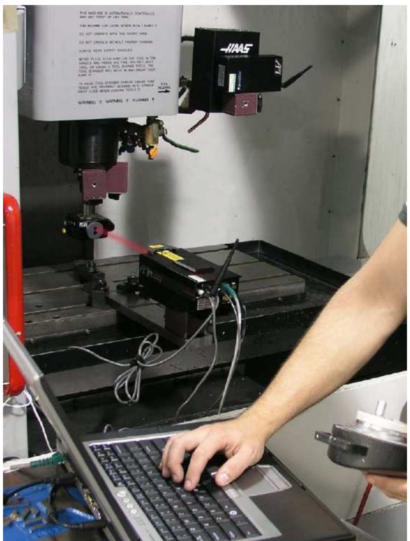
Time required < 3 hours

Ball beam method (here 2D ball beams)



Ball beam positions for a
Portal and Gantry Type mac

API's XD-Laser, a direct 5-degrees-of-freedom measuring system



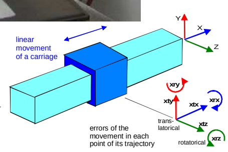
Videos!

Straightness Measurement		
Straightness measurement range:	±0.3mm	±0.3mm
Straightness accuracy:	±(0.5µm + 0.1µm/m) or 1% of max measured error	±(0.5µm + 0.1µm/m) or 1% of max measured error
Straightness resolution:	0.1µm	0.1µm
Measurement Distance:	25m	25m
Squareness Measurement		
Accuracy:	±(1.0 arcsec + 0.2 arcsec/measured travel in meters)	±(1.0arcsec + 0.2 arcsec/ measured travel in meters)
Angularity Measurement		
Measurement range:	±400 arcsec	±400arcsec
Angular resolution:	0.1 arcsec	0.1 arcsec
Measurement Distance:	25m	25m
Pitch and Yaw measurement accuracy:	±(0.5 arcsec + 0.05 arcsec/m) or 1% of max measured error	±(0.5 arcsec + 0.05 arcsec/m) or 1% of max measured error
Roll measurement accuracy (for Horizontal axes only)		±0.5 arcsec or 1% of max measured error
Parallelism Measurement		
Accuracy:		±(1.0 arcsec + 0.2 arcsec/measured travel in meters)

Courtesy:
API

	Max Error Before VEC™	Max Error After VEC™
Machine 1	0.0167 in (0.424 mm)	0.0077 in (0.196mm)
Machine 2	0.0394 in (1.000 mm)	0.0015 in (0.039 mm)
Machine 3	0.0064 in (0.162 mm)	0.0016 in (0.041 mm)
Machine 4	0.0208 in (0.527 mm)	0.0035 in (0.088 mm)
Machine 5	0.0121 in (0.306 mm)	0.0036 in (0.091 mm)

Equivalent to:

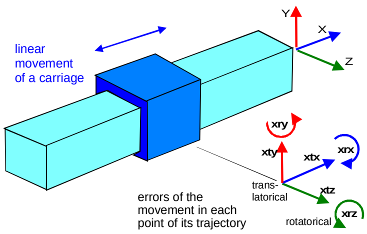


Renishaw’s new 6 degree of freedom measuring device.

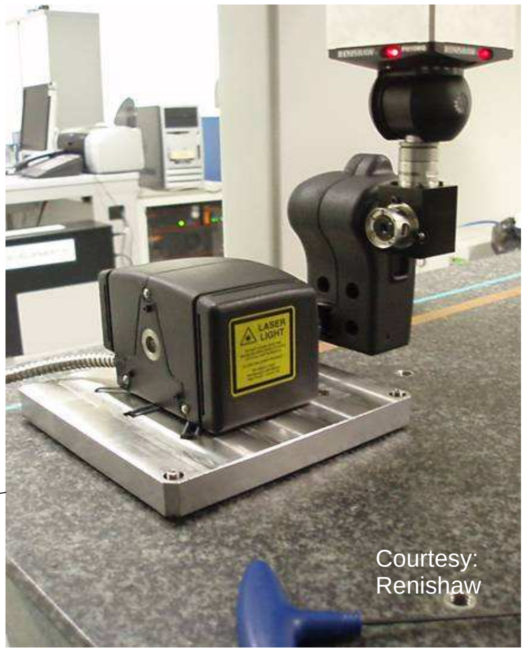
RENISHAW’s brand new
6-degrees-of-freedom
error measuring system

working title: “6-dof”

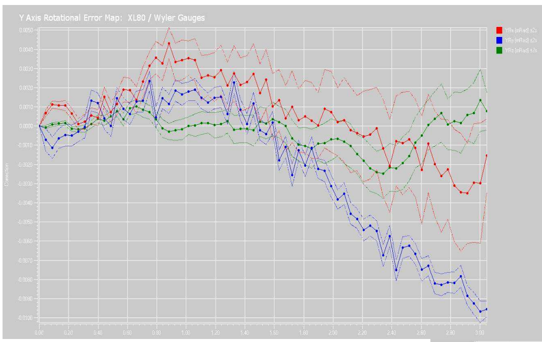
It is so far UCC2-dependent.
This is an advantage as far as automatization is concerned, there is no need for precise alignment (machine follows laser); head size is aprox.
60mm x 60mm x 60mm

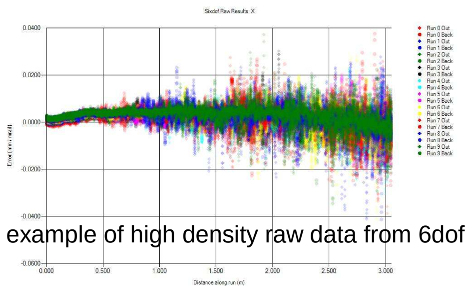


Equivalent to

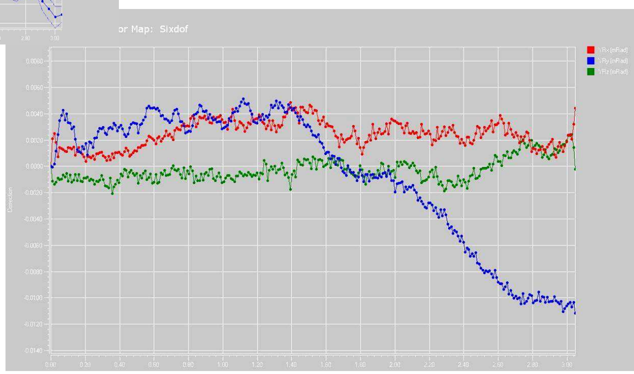


Renishaw’s new 6 degree of freedom measuring device.





example of high density raw data from 6dof

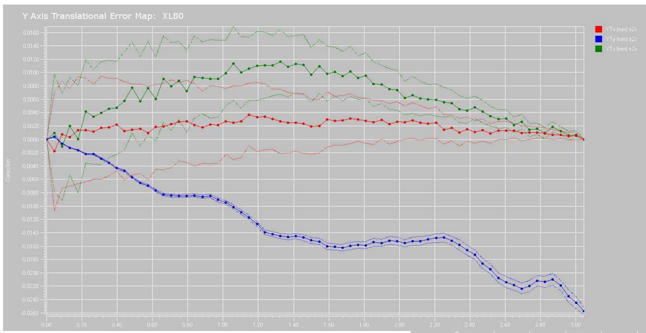


“classical” measurement
of rotatorical errors

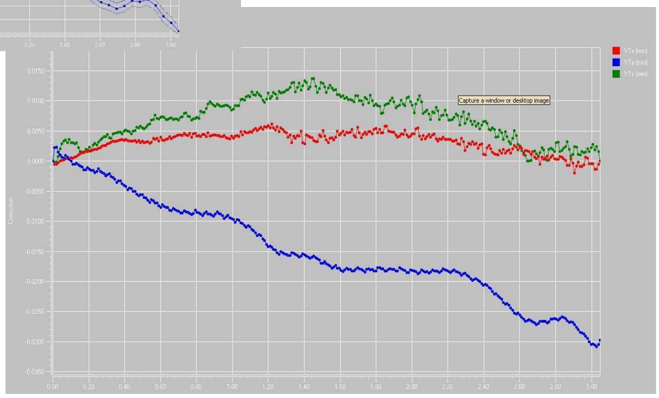
corresponding
6dof measurement

Courtesy:
Renishaw

Renishaw's new 6 degree of freedom measuring device.



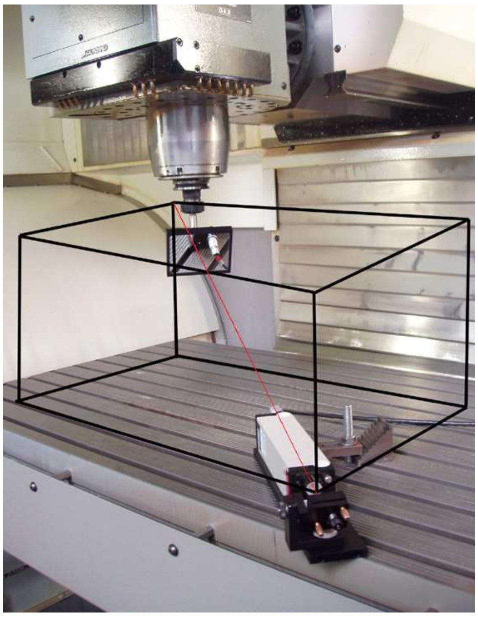
"classical" measurement of translatorical errors

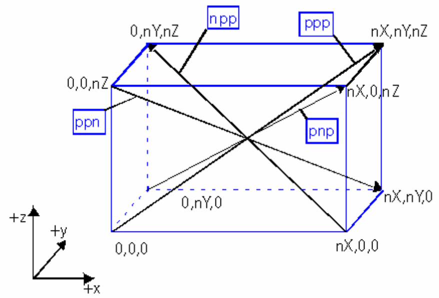


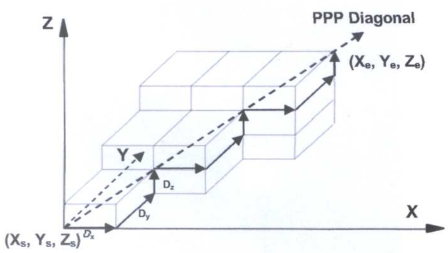
corresponding 6dof measurement

Courtesy: Renishaw

Optodyne's laser vector measuring device.

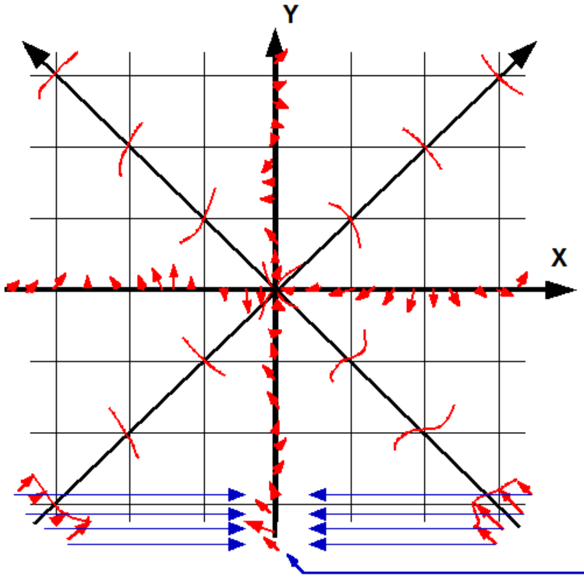






Courtesy: Optodyne

Optodyne's laser vector measuring device.



Optodyne
Laser Vector Method

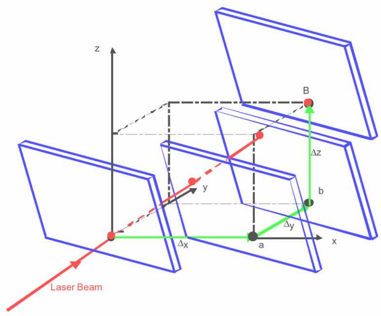
simplified interpretation
of the principle in 2D,
by E.Trapet

note that this method is
capable to analyze errors
in 3D (4 space diagonals)

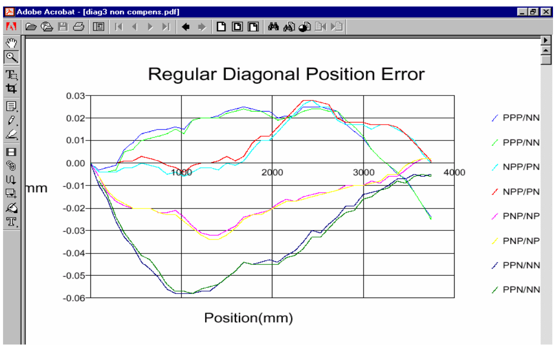
vector sum yields an
average error vector
valid for the center of
the measuring volume

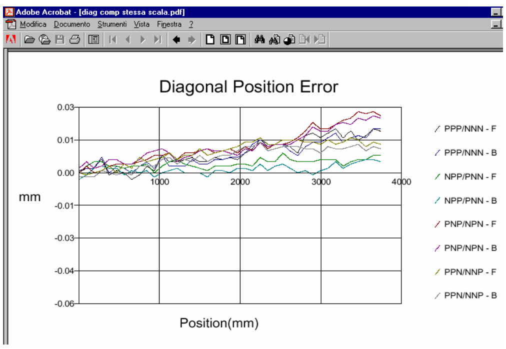
Optodyne's laser vector measuring device.

Results:
- straightness errors
  Dy(x), Dz(x), Dx(y), Dz(y), Dx(z), Dy(z)
- squareness errors
  Bxy, Bzx, Byz
- diagonal displacement test
  Ed



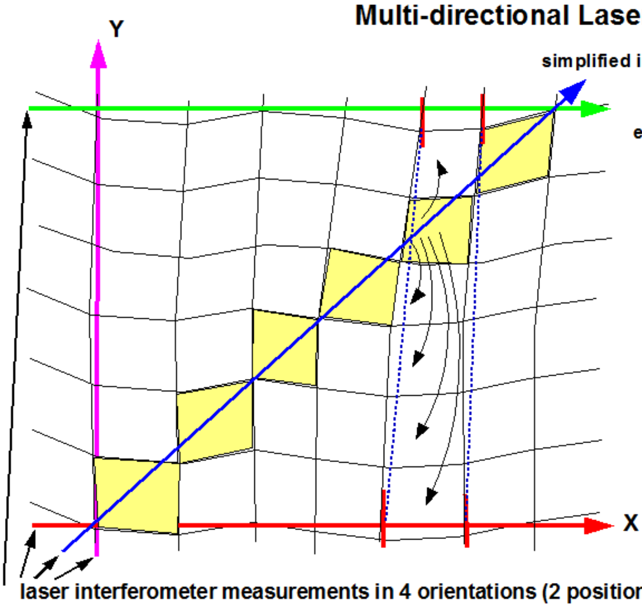
Courtesy:
Optodyne





Using only one linear interferometer for 21 error measurement

Multi-directional Laser Interferometer Method

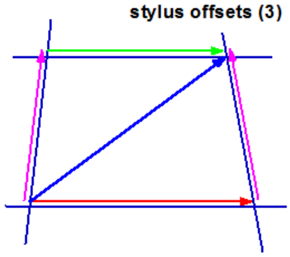


simplified interpretation of the principle in 2D

this method is capable to analyze errors in 3D (5 x 2D measurements, not all need to be complete)

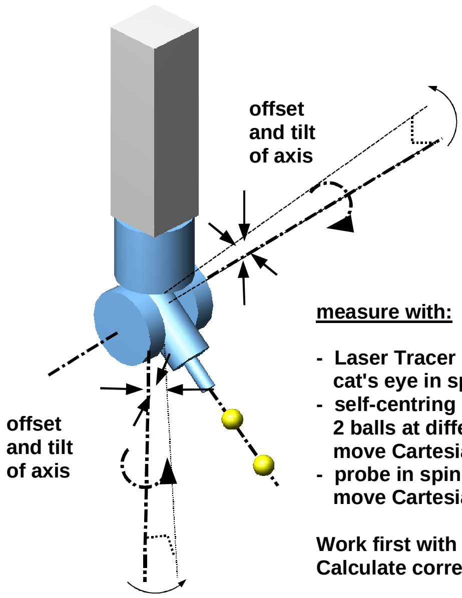
normally more diagonals are measured and best fit is applied

part of the measurements repeated with different stylus offsets (3)



laser interferometer measurements in 4 orientations (2 positions)

Measuring the errors of the rotary heads of CMMs and og 5 axis machine tools

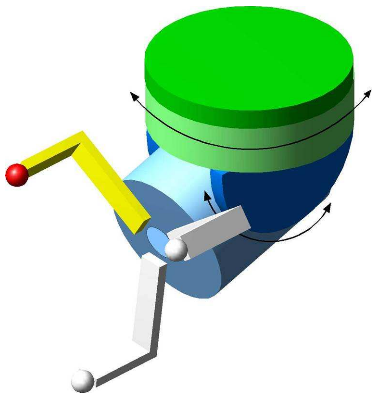


measure with:

- Laser Tracer on machine table,
  cat's eye in spindle, move head around Tracer
- self-centring probe on machine table,
  2 balls at different distance in spindle chuck
  move Cartesian axes and head axes
- probe in spindle, ball on table,
  move Cartesian axes and head axes

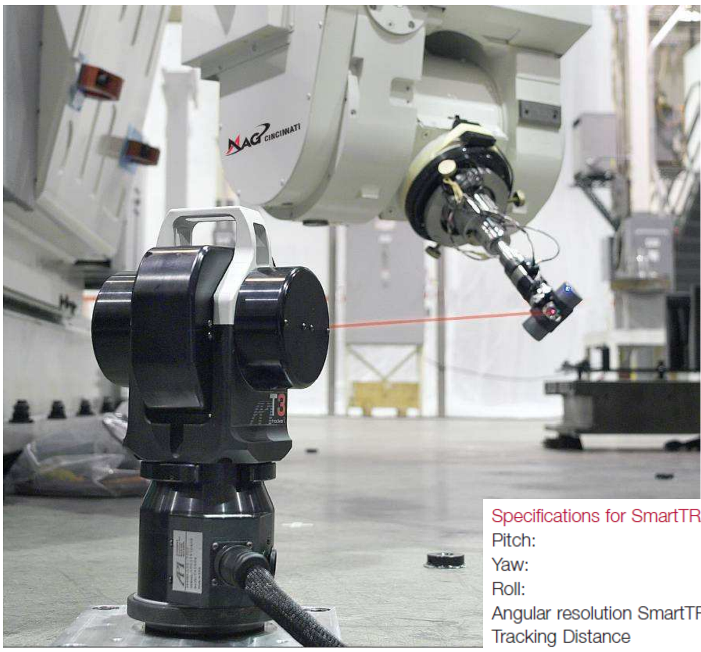
Work first with aproximated values for axis locations.
Calculate corrections as circle or axis tilt and centre offset.

Measuring the errors of the rotary heads of CMMs and og 5 axis machine tools



Courtesy: FIDIA

API's Smart Track System measures 6 degrees of freedom at once



Videos!

Here the Smart Track is measuring head errors, i.e. first of all head axes position and orientation

As well the 21 or more errors of Cartesian axes can be measured too

Courtesy: API

Specifications for SmartTRACK™ Sensor	
Pitch:	± 55°
Yaw:	± 140°
Roll:	± 30°
Angular resolution SmartTRACK™ Sensor:	± 3 arc-sec
Tracking Distance	40 meters

Verifying a correction and maintaining a correction valid

Not all error measurement methods are suited to verify the same errors measured for the exactness of their correction:

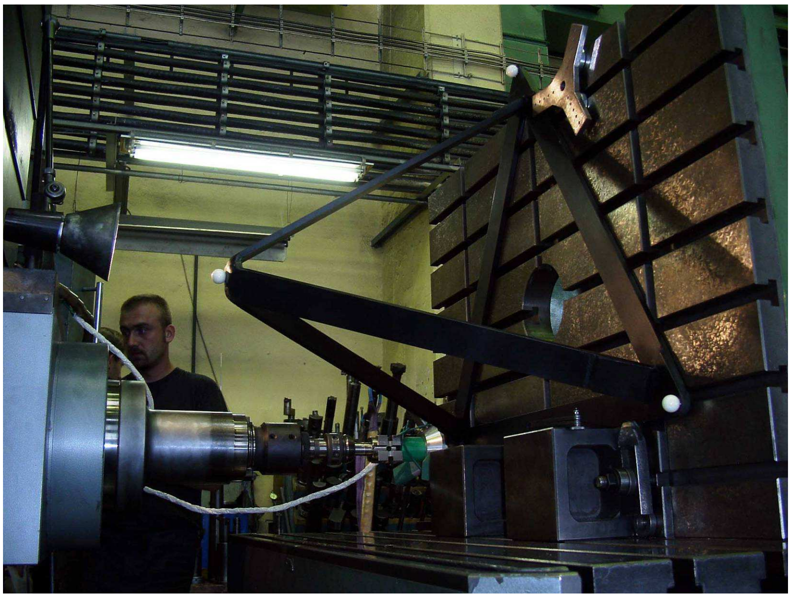
Laser displacement interferometers, straightness measuring systems, and direct distance measuring systems as well as artefacts are well suited

Machine design may substantially favour the accuracy of correction measurements, the stability of errors over time and facilitate the use of the corrected machine

Most important a design taking temperature and temperature changes into consideration; Low CTE scales are the most important improvement
…of course together with work piece temperature compensation.
"compensating work piece temperature at the level of uncertainty of 1 ºC is easier than compensating during the calibration of the machine at the level of uncertainty of 0.3 ºC or even when calibrating a steel standard at the level of uncertainty of < 0.1 ºC !"

Reference structures in/on the machine and external reference objects measured e.g. by the machine allow to judge the stability and facilitate low order tuning values (for example for squareness changes and gradient induced pitch)

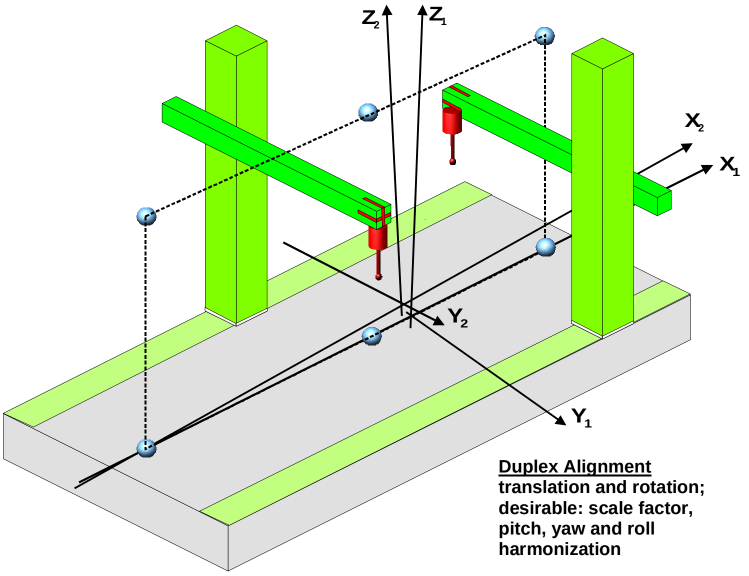
Verifying a correction and maintaining a correction valid



Use of simple artifacts, measured with the machine,

here: ball-tetrahedron

Maintaining a correction valid
Here: duplex alignment (re-alignment by user)



Duplex Alignment
translation and rotation;
desirable: scale factor,
pitch, yaw and roll
harmonization

Conclusions

For CMMs the "full" correction exists since about 30 years and is indispensable today for the accuracy;
On site calibration become more feasible with the new calibration methods and thus a higher accuracy for a larger number of CMMs;

This goes hand in hand with more thermally stable designs of the CMMs and with the capability of the user to monitor his machine accuracy (artefacts)

The "full scale" correction of machine tools has just started and has great potential still, many controllers have full error correction now, for high accuracy part machining it is already indispensable.

In order to monitor the machine tool accuracy the users will more and more rely on periodic verifications (e.g. by artefact measurement)

Correction parameter measurement has evolved from a tedious job of 1 week to a profitable 1 day's job (profitable for service and client)