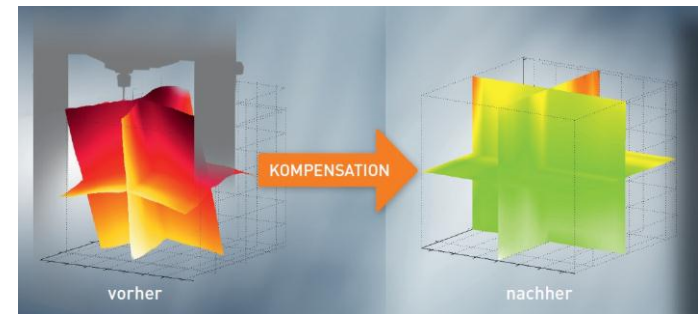
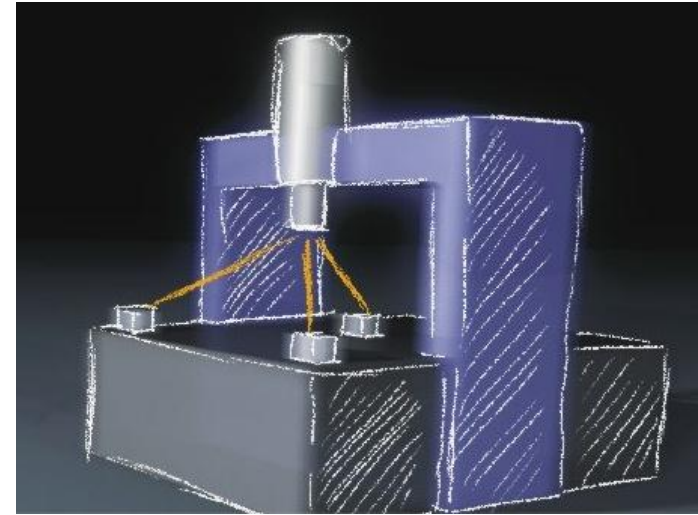
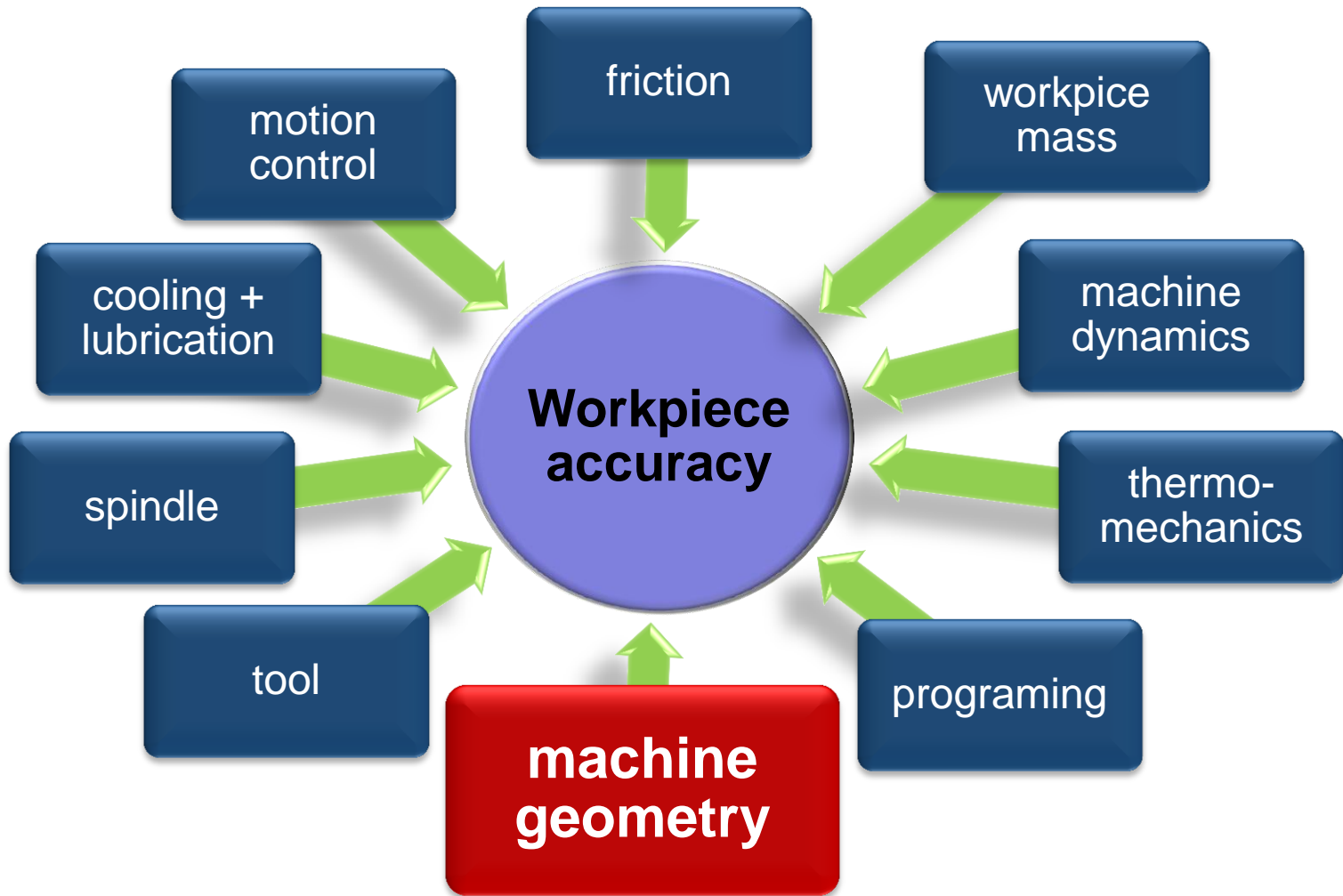


# The latest trends and future possibilities of volumetric error compensation for machine tools

- ▷ Errors of machine tools
- ▷ Kinematic chain
- ▷ Conventional measurements
- ▷ Etalons Multilateration approach
- ▷ Compensation of machine tools
- ▷ Standardization
- ▷ Conclusion and Outlook



# What can influence the workpiece accuracy?

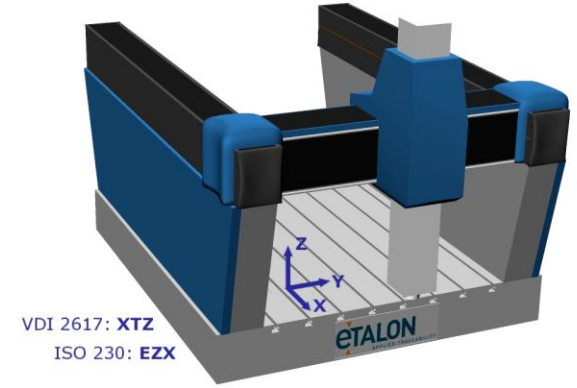
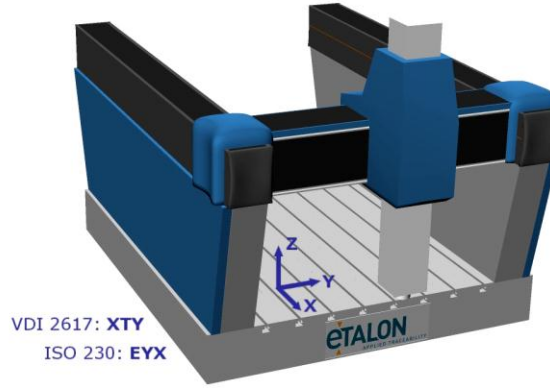
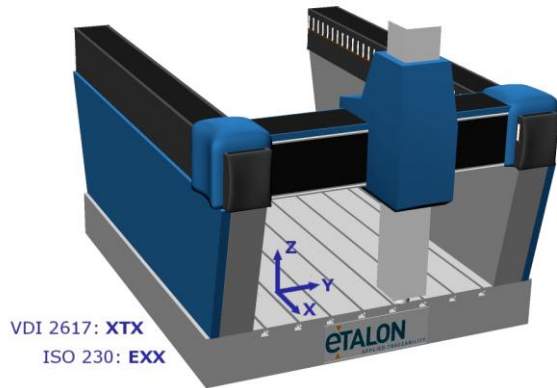


# Systematic machine errors : Example x-axis

Position: EXX

Straightness 1: EYX

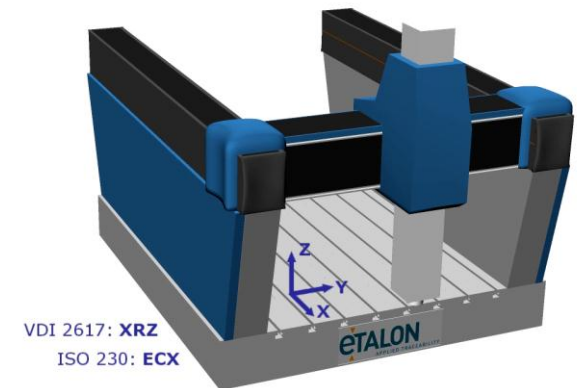
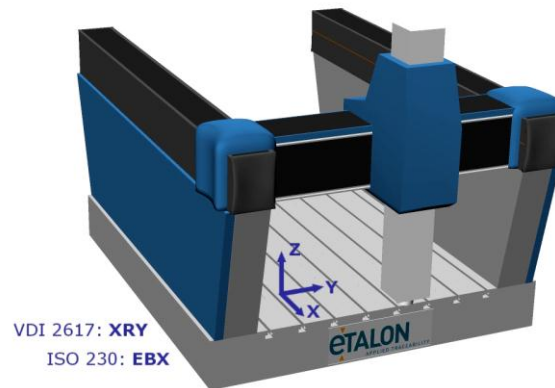
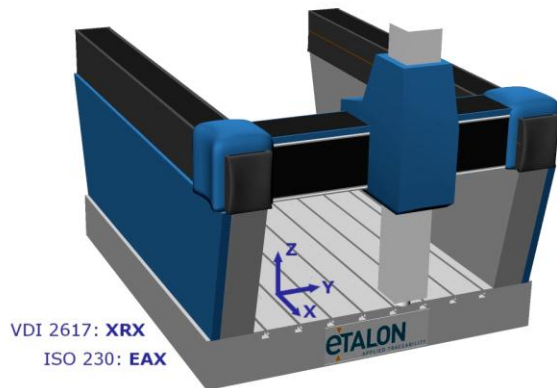
Straightness 2: EZX



Roll: EAX

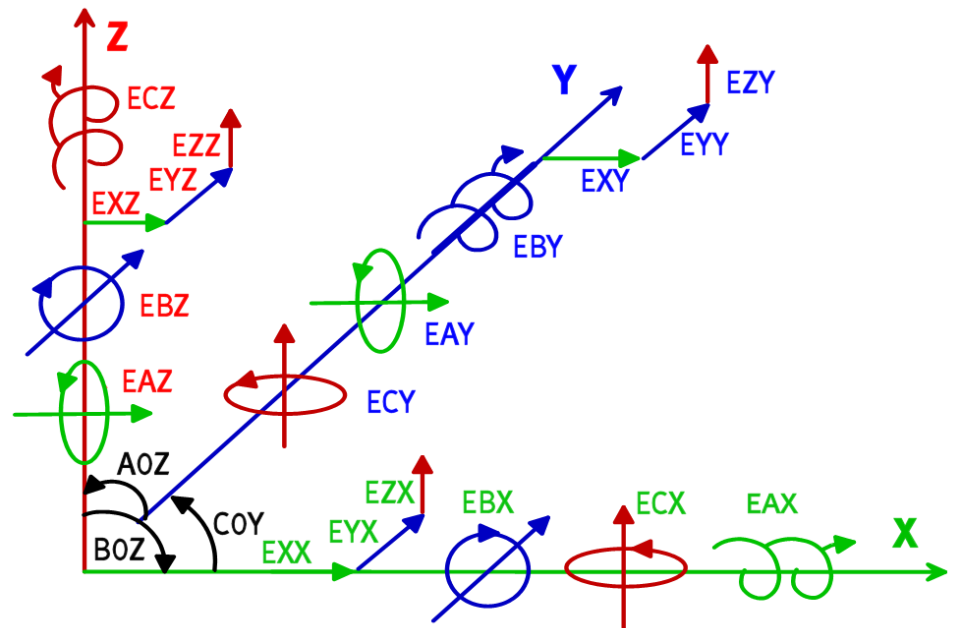
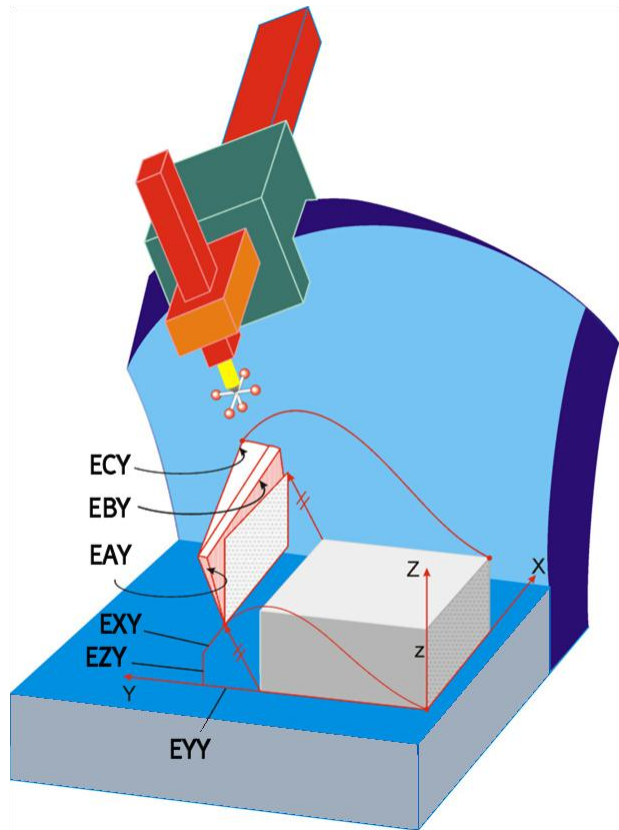
Pitch: EBX

Yaw: ECX

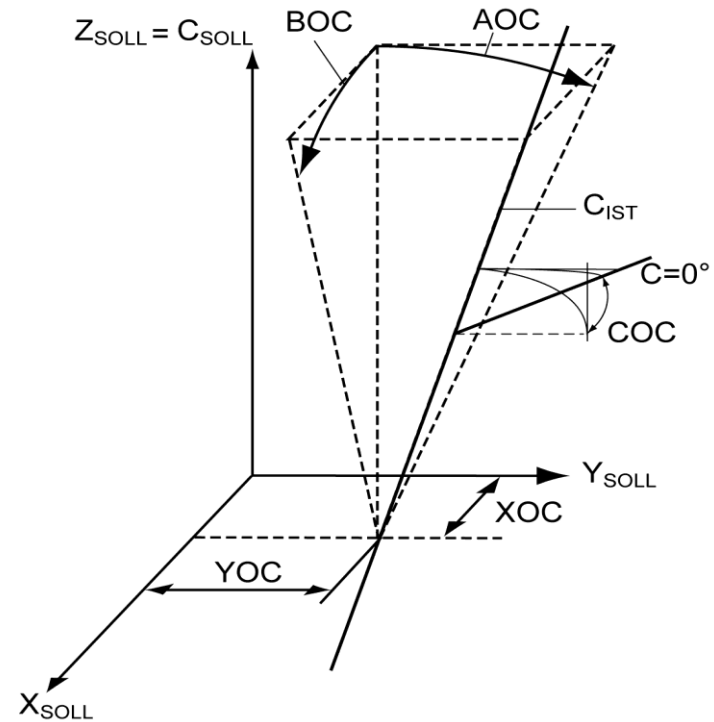
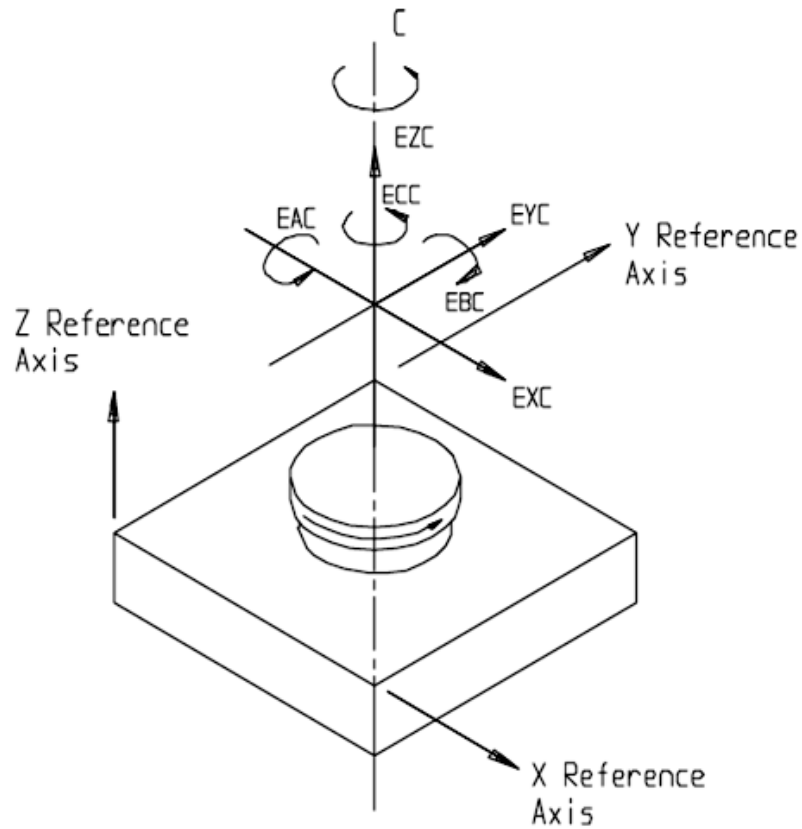


# Geometry deviations of a Cartesian Machine

(notation according to ISO 230)

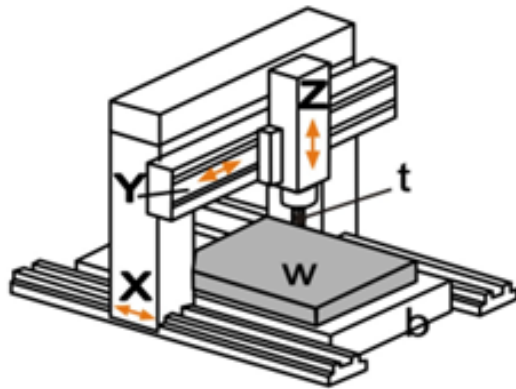


# Geometry deviations of a Rotary axis (notation according to ISO 230)



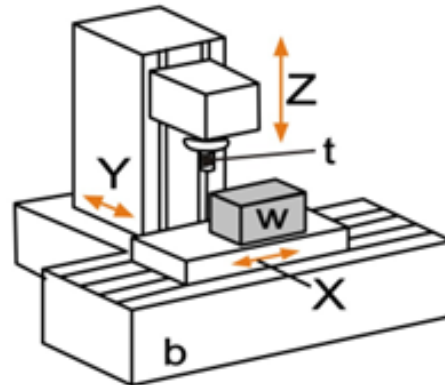
**Different kinematic chain, on which this systematic can be applied (not exhaustive)**  
 (description of kinematic chain according to ISO 230-1)

Portal / Gantry-type



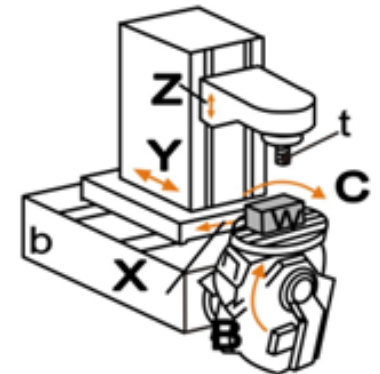
t - (C) - Z - Y - [X1 X2] - b - w

Column-type



t - (C) - Z - Y - b - X - w

5 axes machine



t - (C) - Z - Y - X - b - B - C - w

## Direct measurement: Position errors



© Agilent

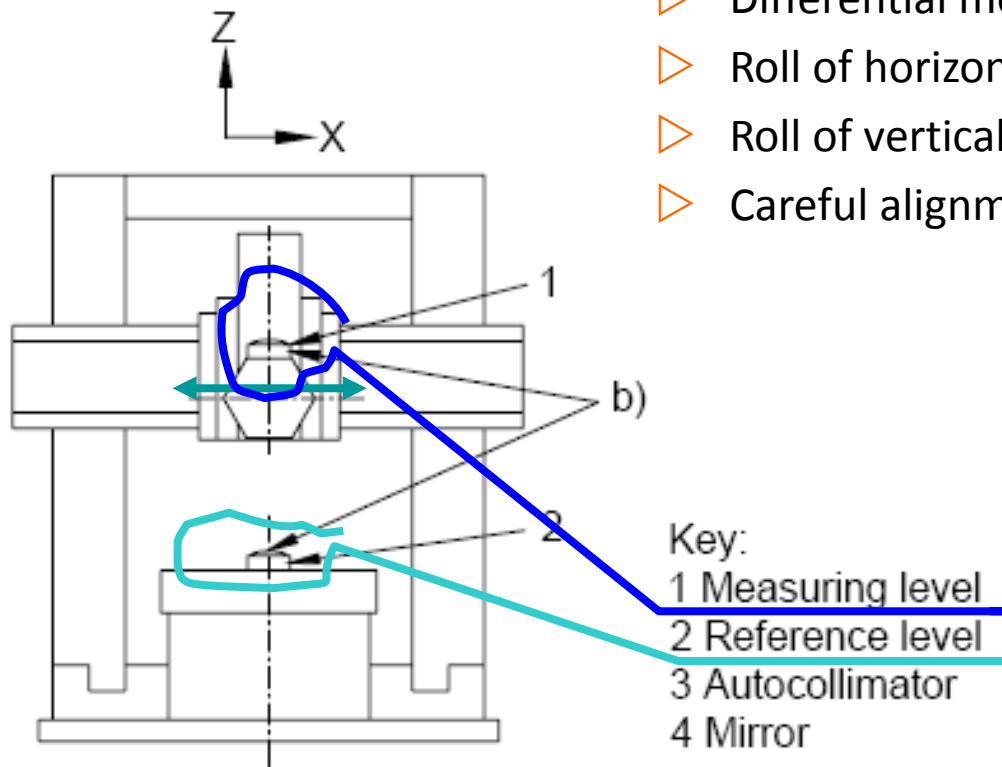
### Use of interferometers or calibrated standards (e.g. glass scales)

- ▷ High accuracy
- ▷ Careful alignment necessary
- ▷ Standards procedure in machine tool metrology

## Direct measurement: Angular errors

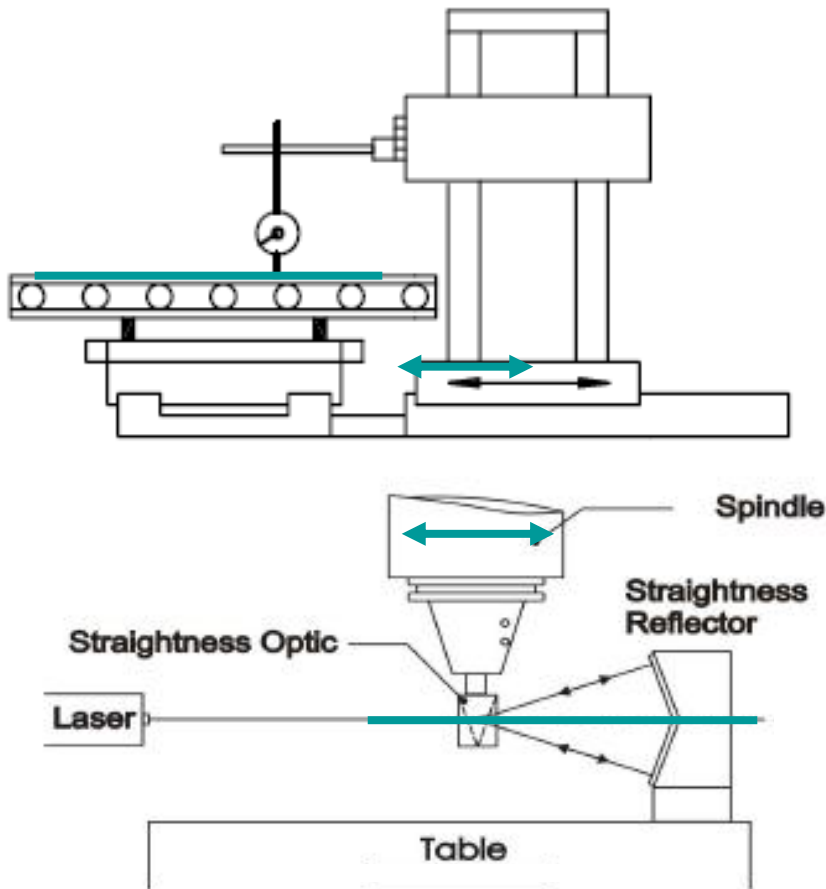
### Use of electronic levels or angle interferometers

- ▷ Differential measurement necessary
- ▷ Roll of horizontal axes can only be measured by levels
- ▷ Roll of vertical axes cannot be measured directly
- ▷ Careful alignment necessary



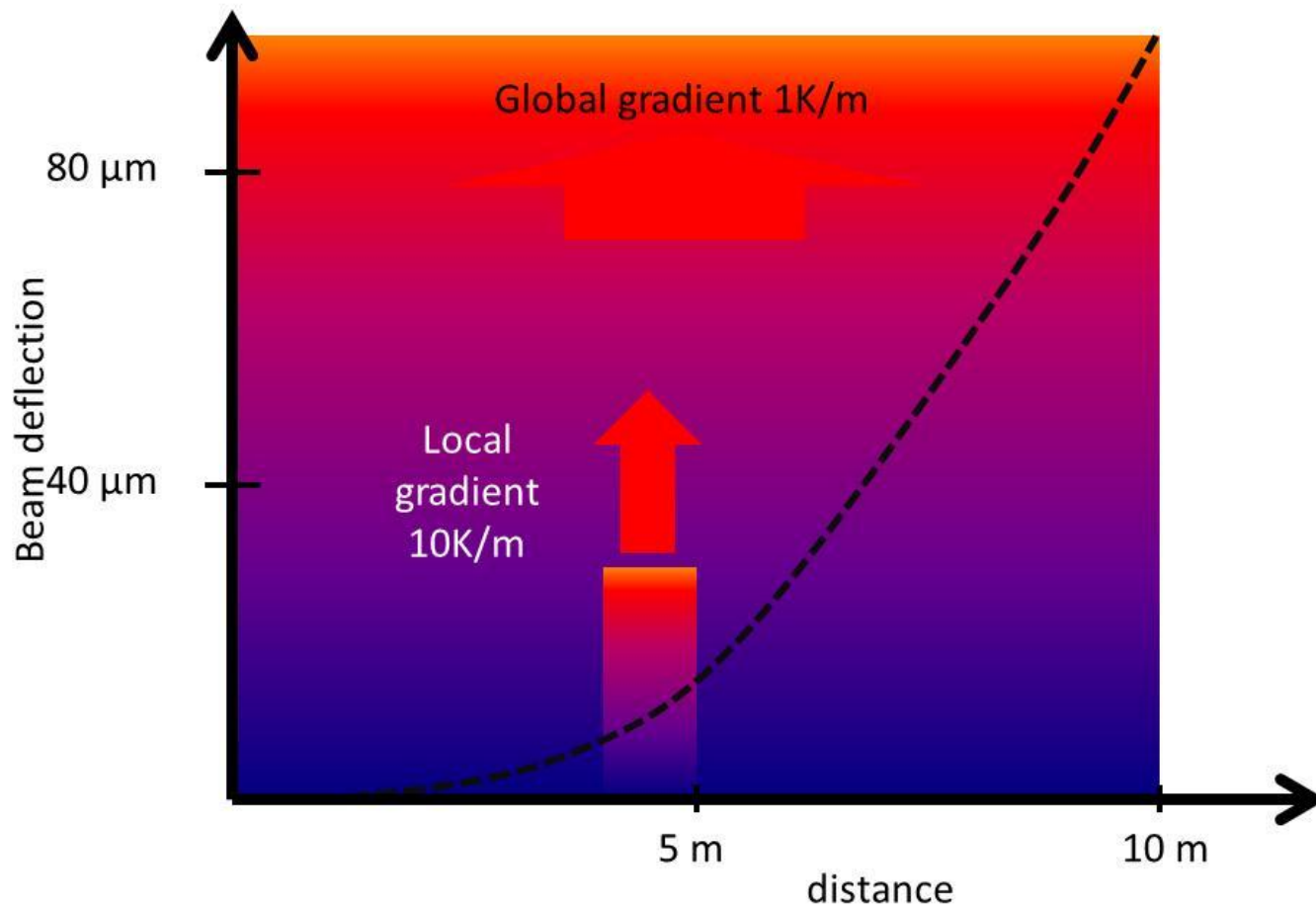


## Direct measurement: Straightness errors



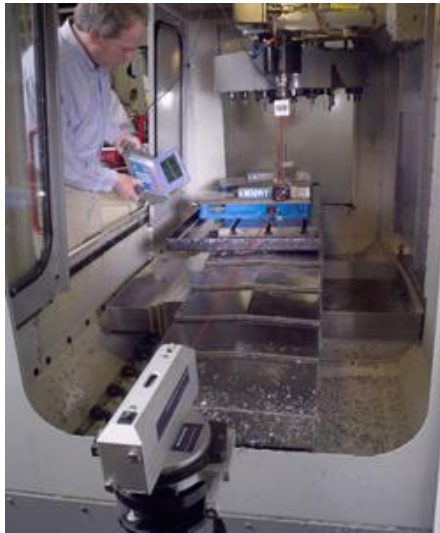
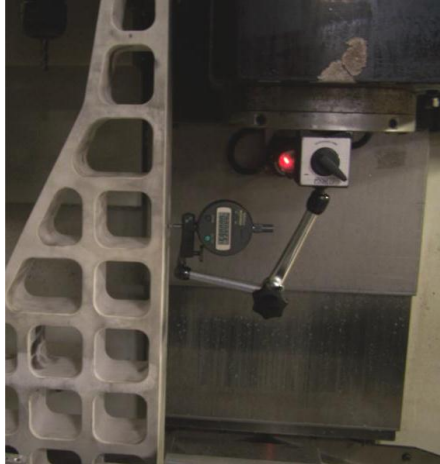
### Use of straightedges or interferometer in Wollaston Prism and wedge shaped reflector

- ▷ Calibration and setup of straight edge challenging (bending)
- ▷ Straightedges must have fitting proportions for all axes
- ▷ Laser straightness: Strong environmental influence
- ▷ Set up of laser straightness for long distances very challenging



**A laser beam is a poor straightness standard in industrial environment !**

## Direct measurement: Squareness errors



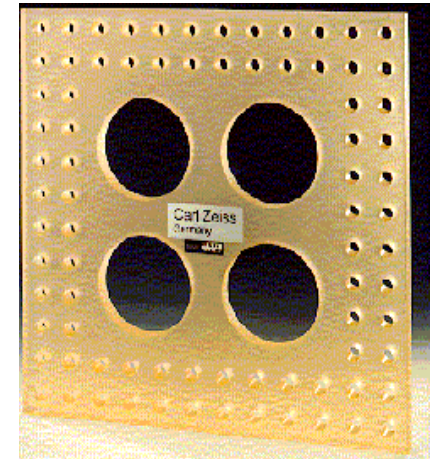
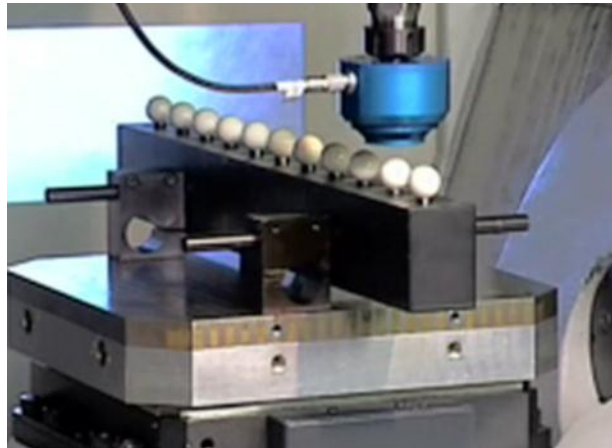
- (1) Use of square standard
- (2) interferometer with pentaprism
- (3) Ball bar

- ▷ All methods give only local squareness
- ▷ Square standard must have right proportion
- ▷ Set up of interferometer very challenging and uncertainty relatively high




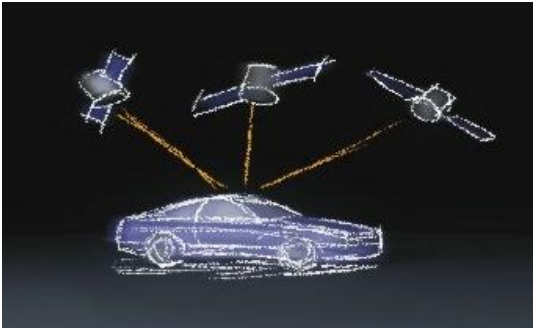

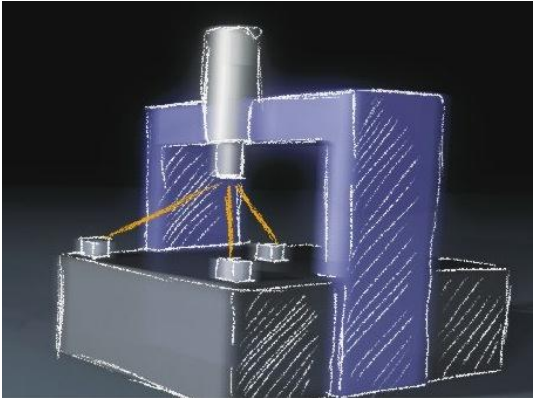
## Calibration based on probing of calibrated artefacts

- Examples: Ball bar, Ball / hole plate.
- Pro: Simple procedure, temperature invariant materials possible.
- Contra: Artefacts must fit to machine volume, clamping of artefacts challenging, minimum sampling interval limited by mechanical reference elements.



# The progress in technology

## - Comparison of calibration with navigation

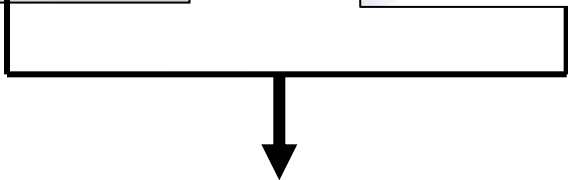
	conventional	new: Multilateration
Navigation		
Calibration and testing		

# The ETALON solution

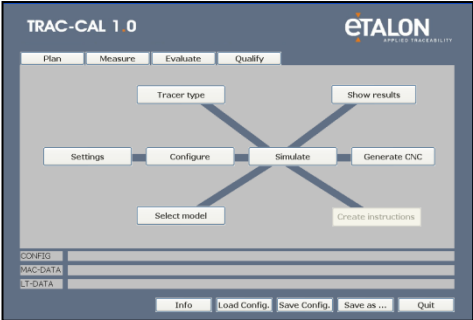
LaserTRACER



LaserTRACER-MT

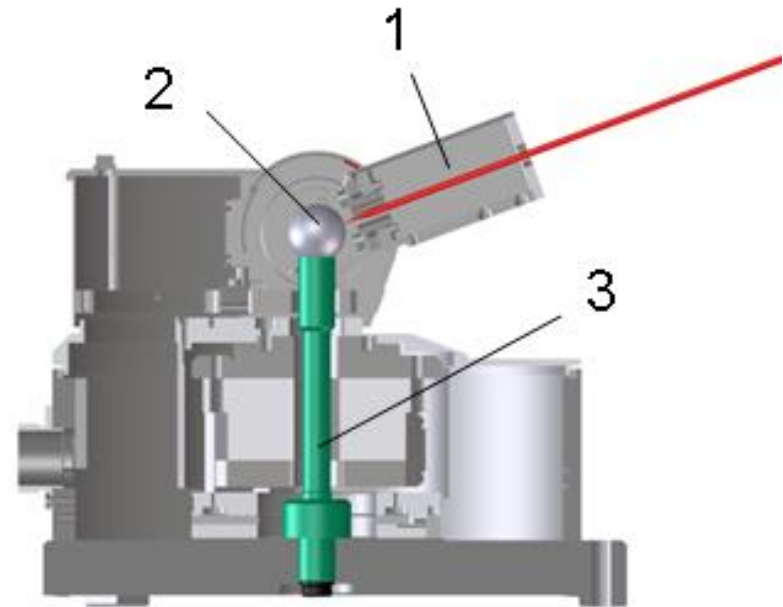


TRAC-CAL<sup>®</sup>



Error mapping and compensation

## The LaserTRACER

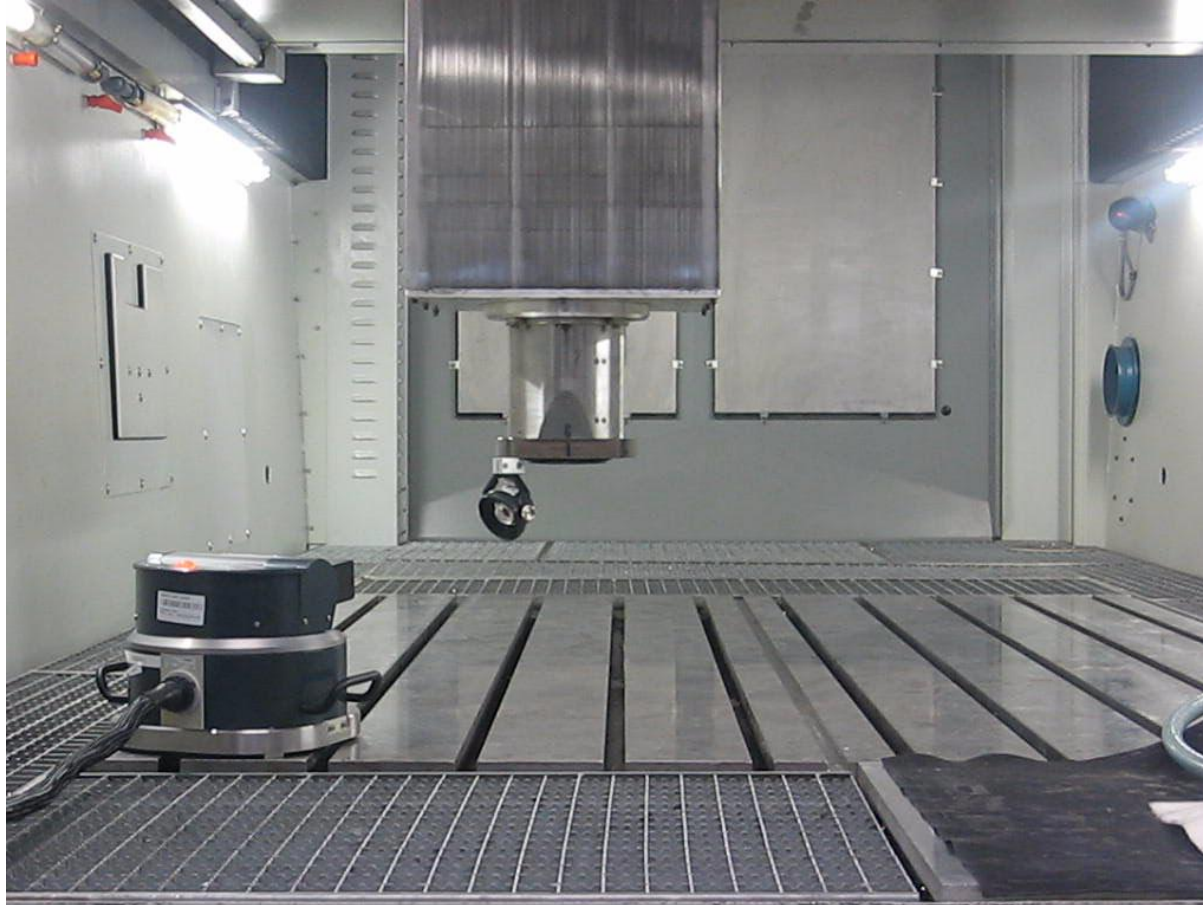


- ▷ Interferometer with  $0,001 \mu\text{m}$  resolution (1)
- ▷ Patented reference sphere (2) with form deviation  $< 0,050 \mu\text{m}$
- ▷ Environmental compensation for temperature, pressure, humidity

 Length measurement uncertainty:  $U = 0.2 \mu\text{m} + 0.3 \mu\text{m}/\text{m}$



# Movie TRAC-CAL





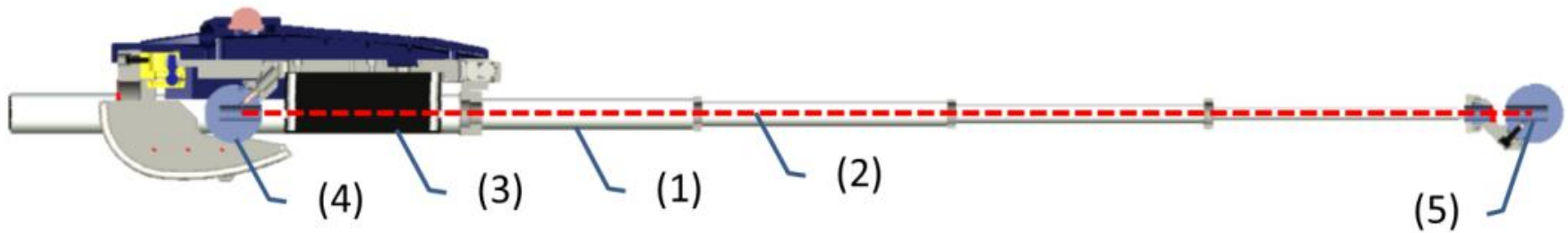
## New: The LaserTRACER-MT (MT: Mechanical Tracking)



- ▷ Passive tracing mechanism of the laser interferometer
- ▷ For small to medium sized machines
- ▷ Based on the same principles as the LaserTRACER
- ▷ Light weight (< 2500 g)
- ▷ Radial working range from 260 mm to 1000 mm
- ▷ Angular working range from  $-35^{\circ}$  to  $+80^{\circ}$  (elevation) and  $>360^{\circ}$ \* (azimuth)
- ▷ The entire software options from Etalon are usable

\* Limitation only by the cable

## The patent pending design of the LaserTRACER-MT



- ▷ (1) Telescope extends to from 260 mm to 1000 mm
- ▷ (2) Measurement beam between center of reference spheres
- ▷ (3) Bidirectional interferometer
- ▷ (4,5) Reference spheres (rest on magnetic cups)

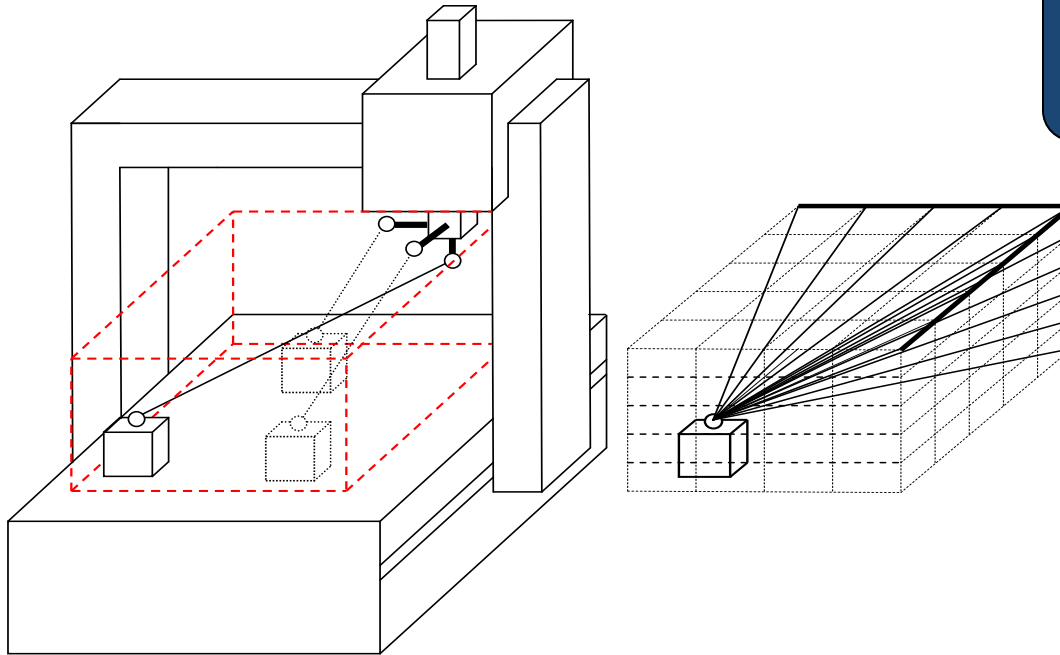
**First measurement run...**



<http://youtu.be/T-PMNCqm4F4>

## The Principle:

“GPS-  
Principles”  
for machine  
calibration



- ▷ Interferometrical length measurement from 4-6 positions
- ▷ **Evaluation of all errors entirely based on length information**
- ▷ Position of LaserTRACER position and dead path need not be known

# Solving a linearized set of equations

$$C_{par} \cdot Par = E$$

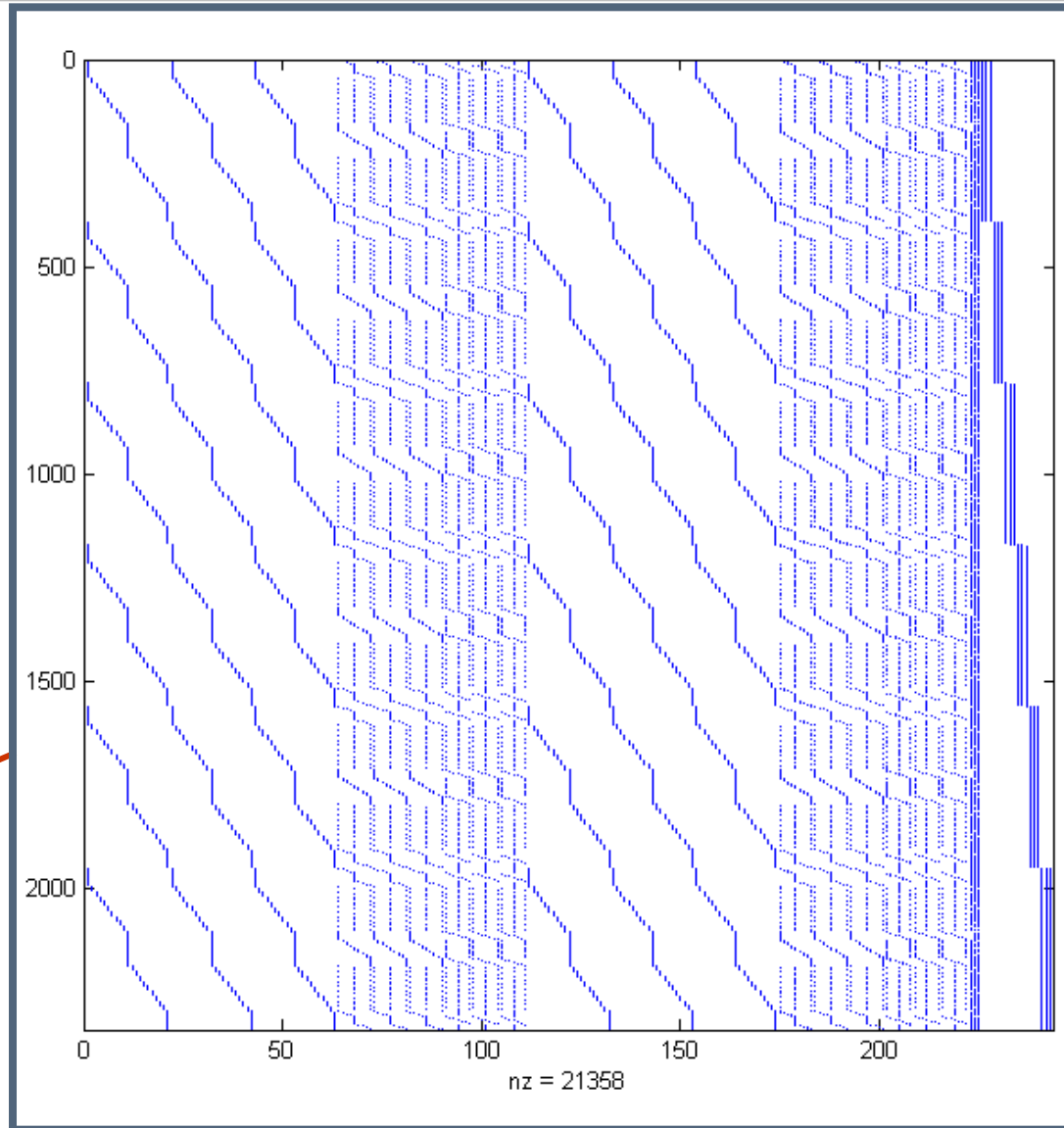
$$(d\Delta P_{Norm} \cdot E)^T \cdot K = \Delta L^T$$

$$(d\Delta P_{Norm} \cdot C_{par}^* \cdot Par^*)^T \cdot K = \Delta$$

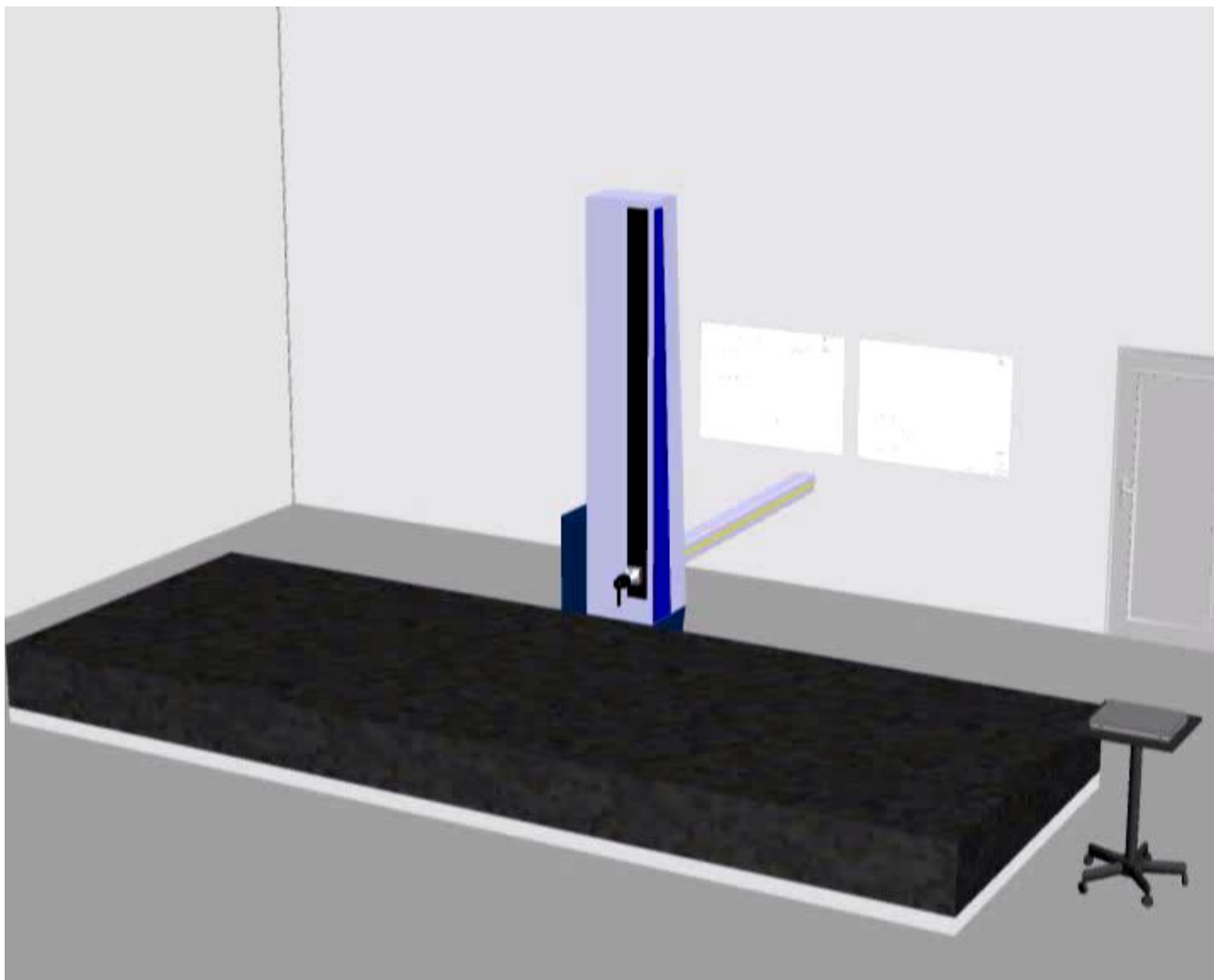
$$(C_{par}^{*T} \cdot d\Delta P_{Norm} \cdot K)^T = M$$

$$\begin{bmatrix} M & C_0 \end{bmatrix} \cdot \begin{bmatrix} Par^* \\ L_0 \end{bmatrix} = \Delta L$$

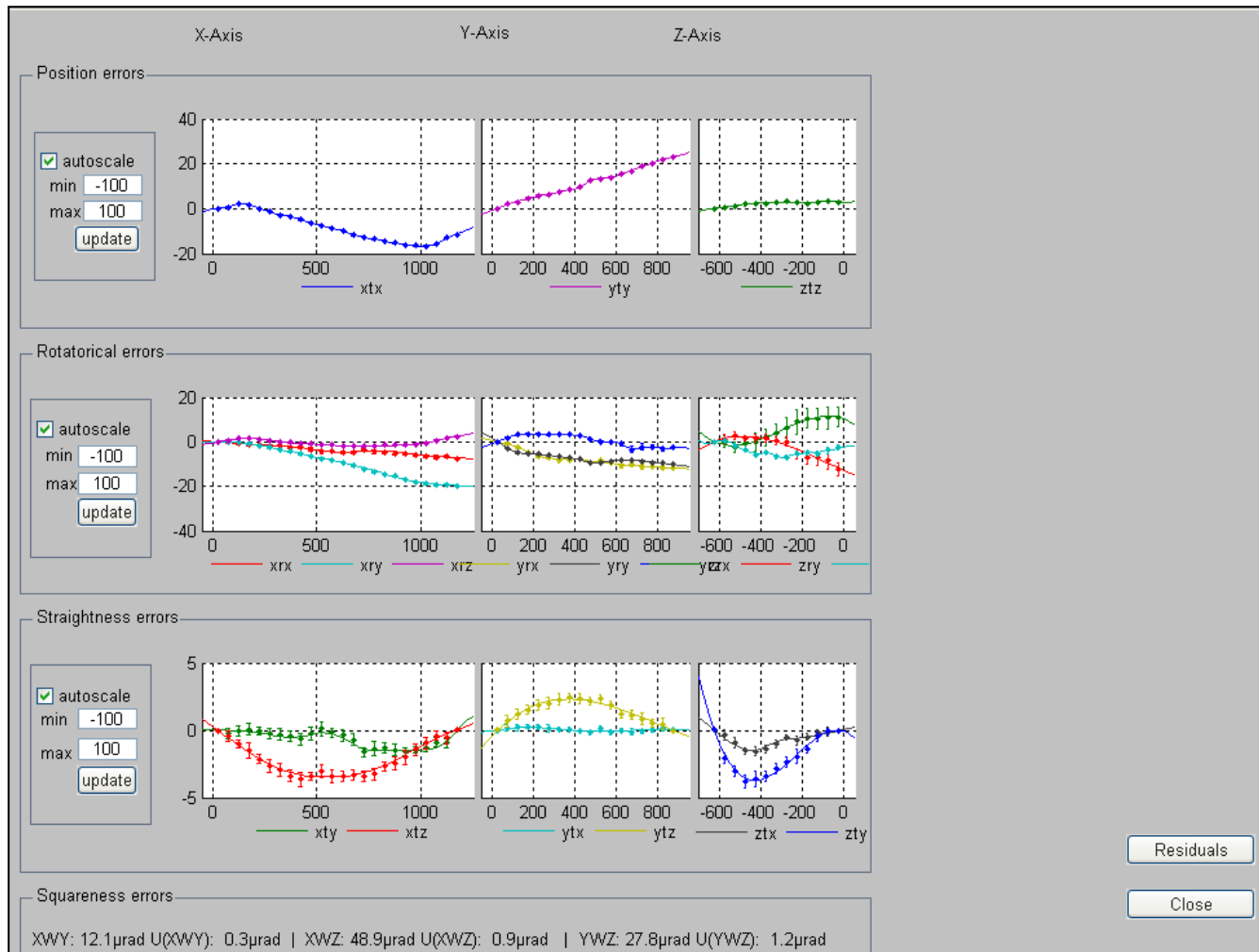
$$\begin{bmatrix} M & C_0 \\ B & 0 \end{bmatrix} \cdot \begin{bmatrix} Par^* \\ L_0 \end{bmatrix} = \begin{bmatrix} \Delta L \\ 0 \end{bmatrix}$$



## How TRAC-CAL works - LINEAR AXES



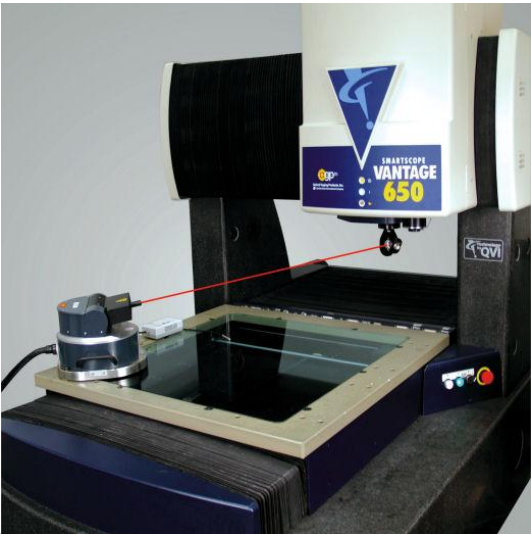
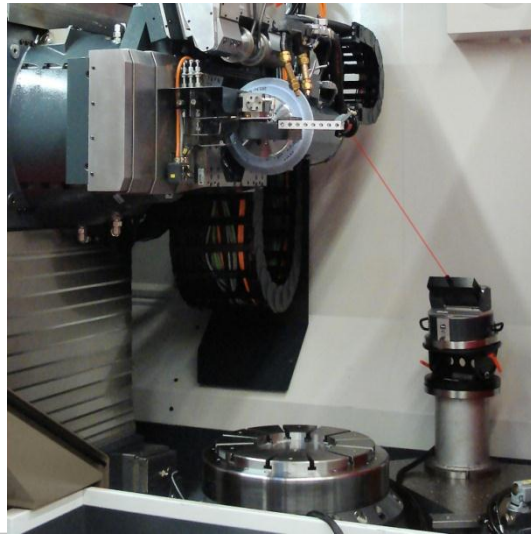
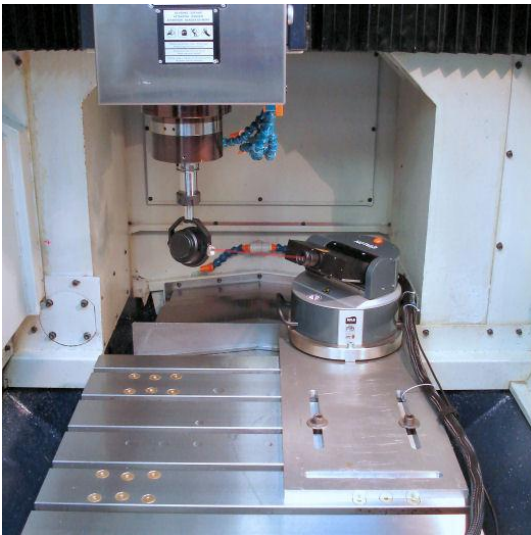
# Evaluation of parametric errors



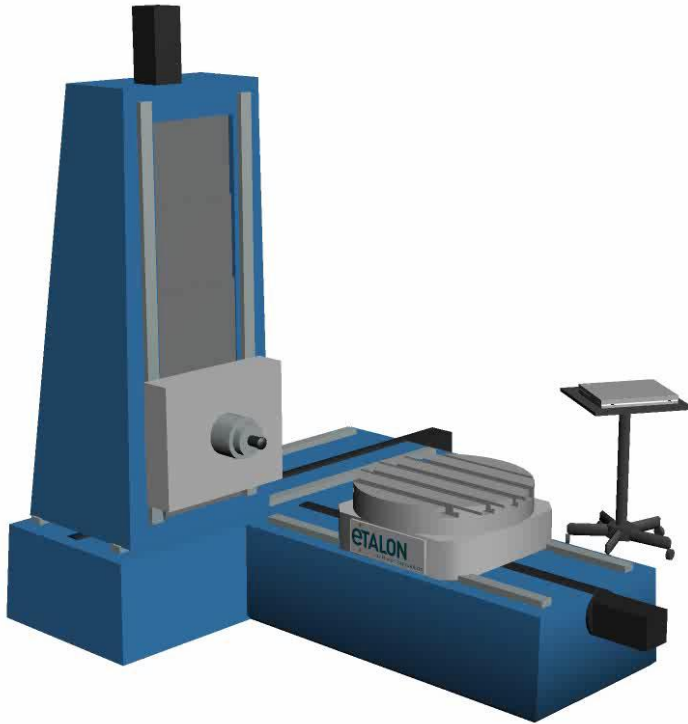
# Horizontal machining center before and after compensation



# Application examples



# Calibration of rotary axes

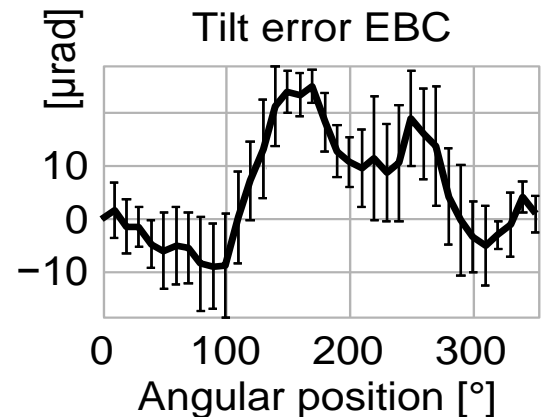
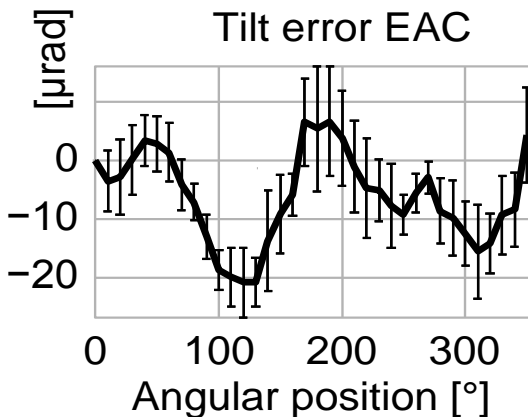
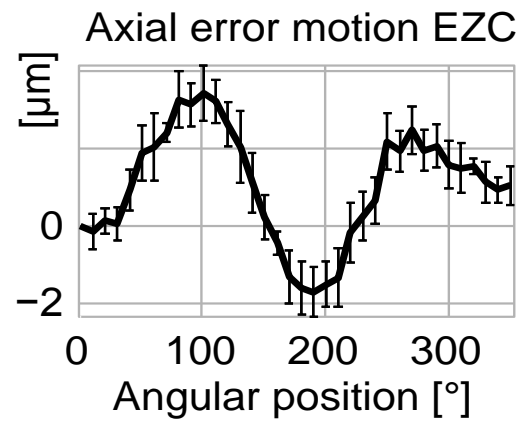
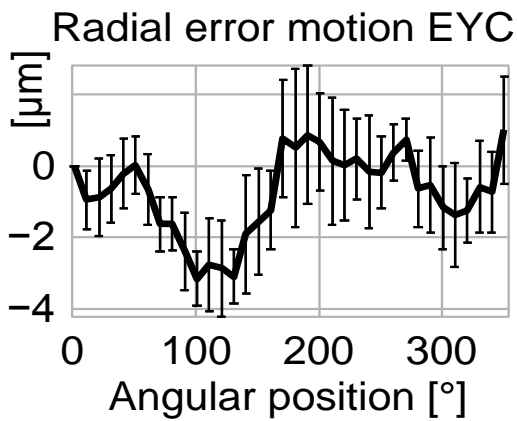
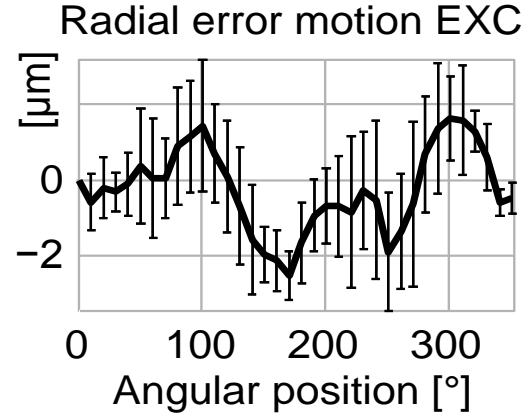
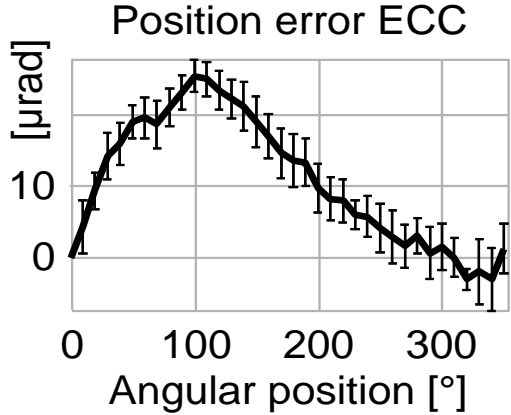
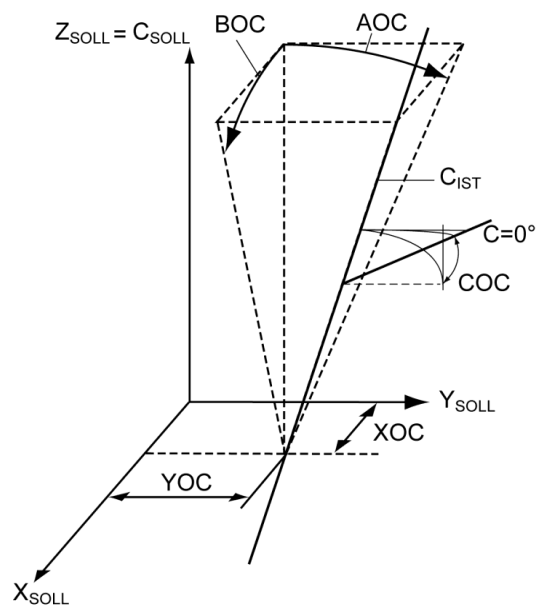
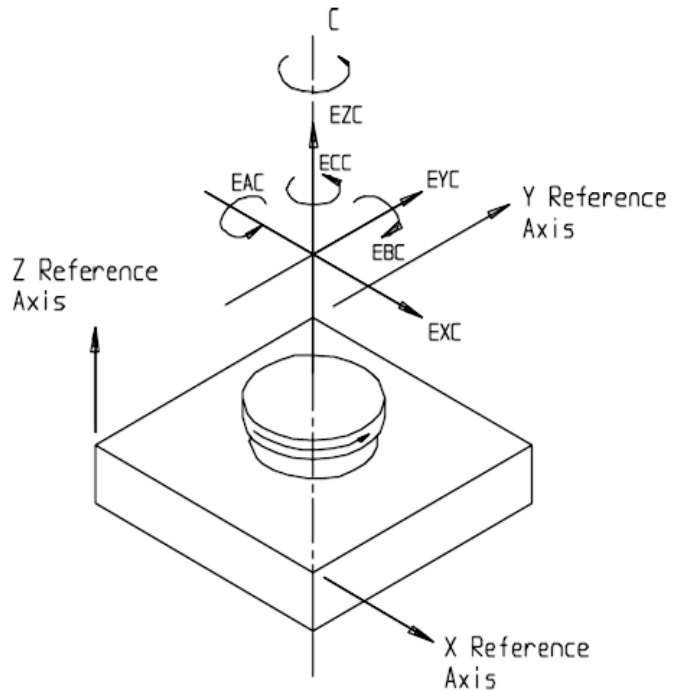


## Determination of

- ▷ Angular positioning
- ▷ Axial motion
- ▷ Radial motions
- ▷ Tilt motions
- ▷ Angular location in the machine volume

## Solely based on interferometric measurements of the LaserTRACER

- ▷ No additional hardware necessary
- ▷ Very high accuracy
- ▷ Easy use
- ▷ Especially suitable for large rotary axes



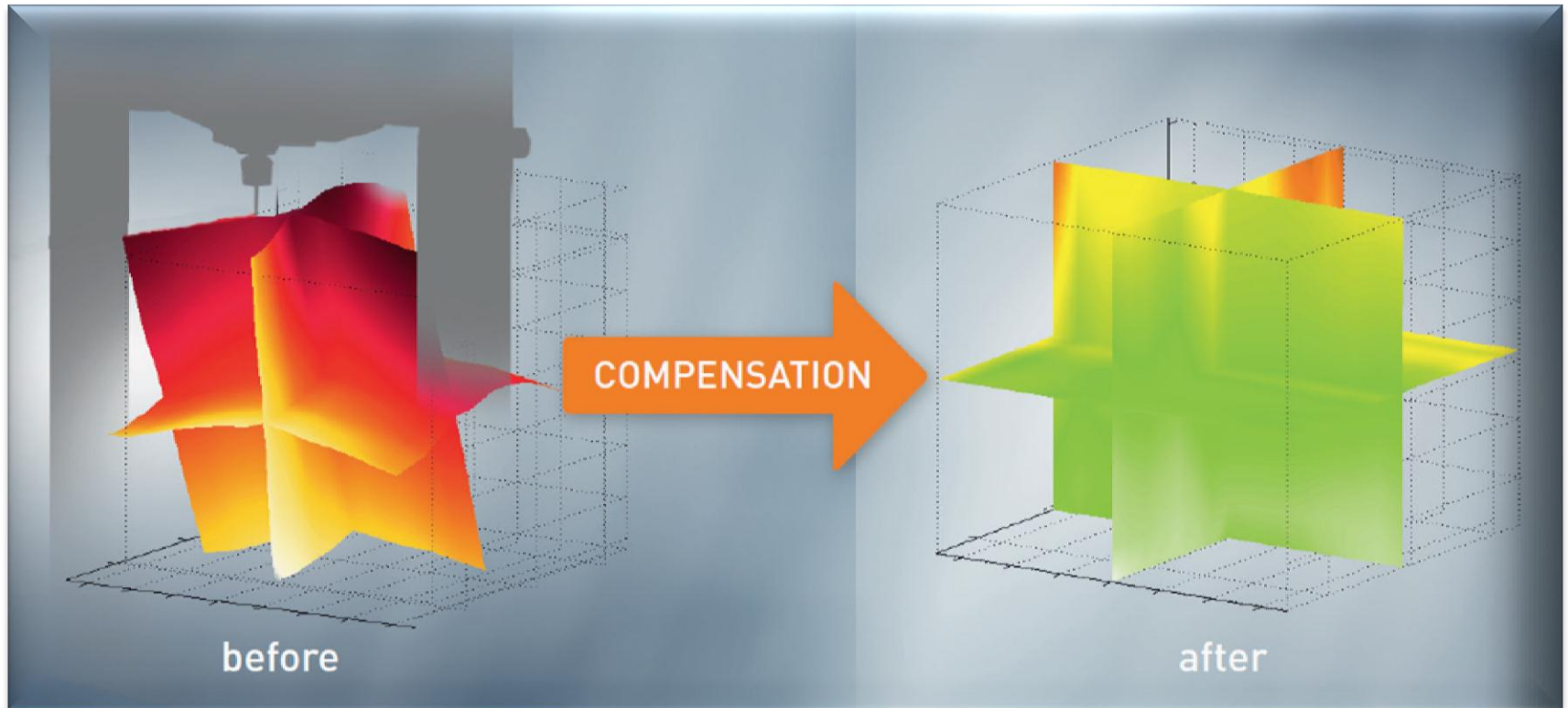
# Measurement of rotary axes: 9 m x 7 m x 3 m machine with 5 m table diameter



# Report rotary table



## Concept of volumetric compensation

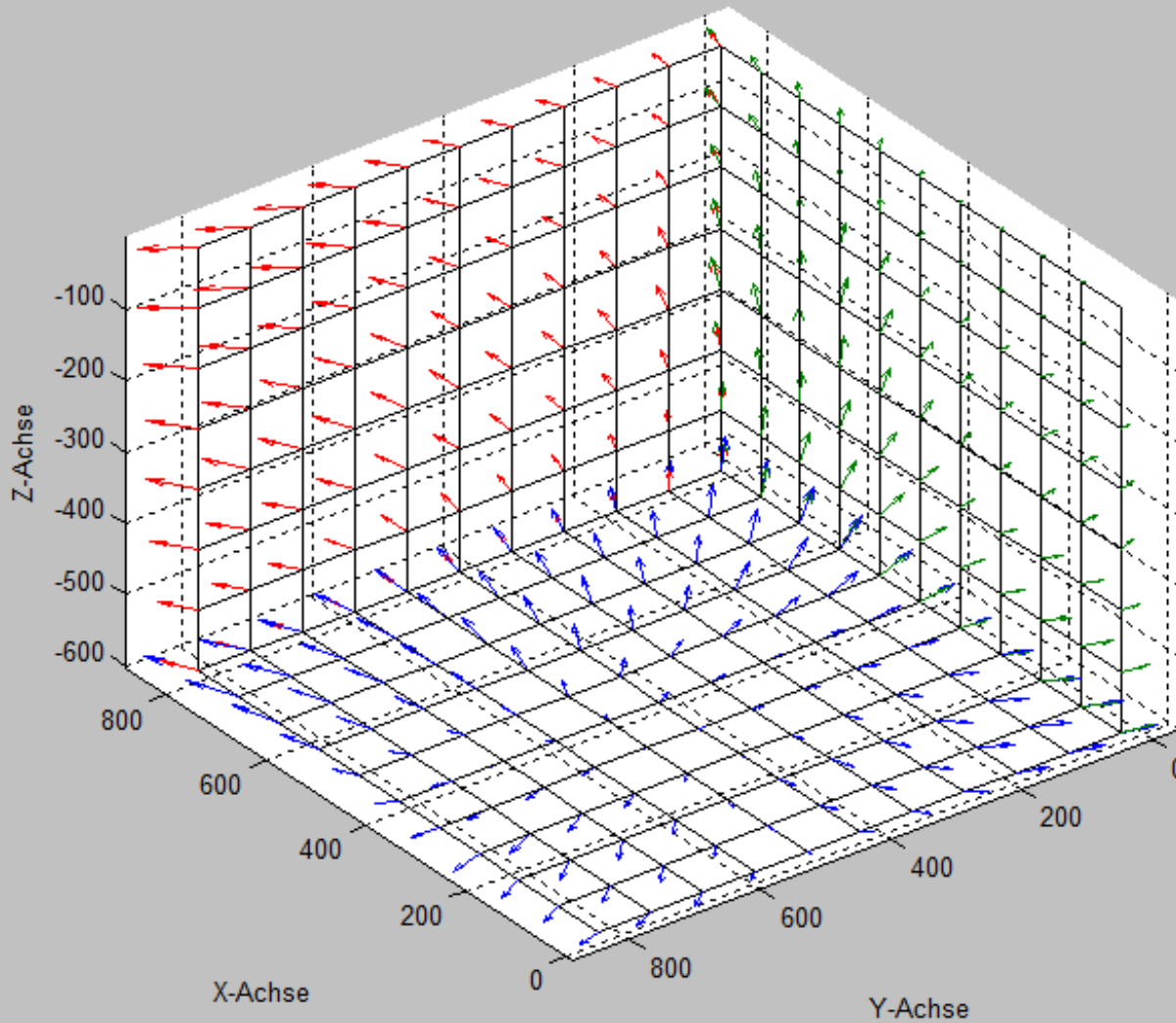


- ▷ Measure the geometry errors in the entire machine volume
- ▷ Use this information to compensate these errors during machining

## Implementation of “volumetric compensation” to machine tool controllers

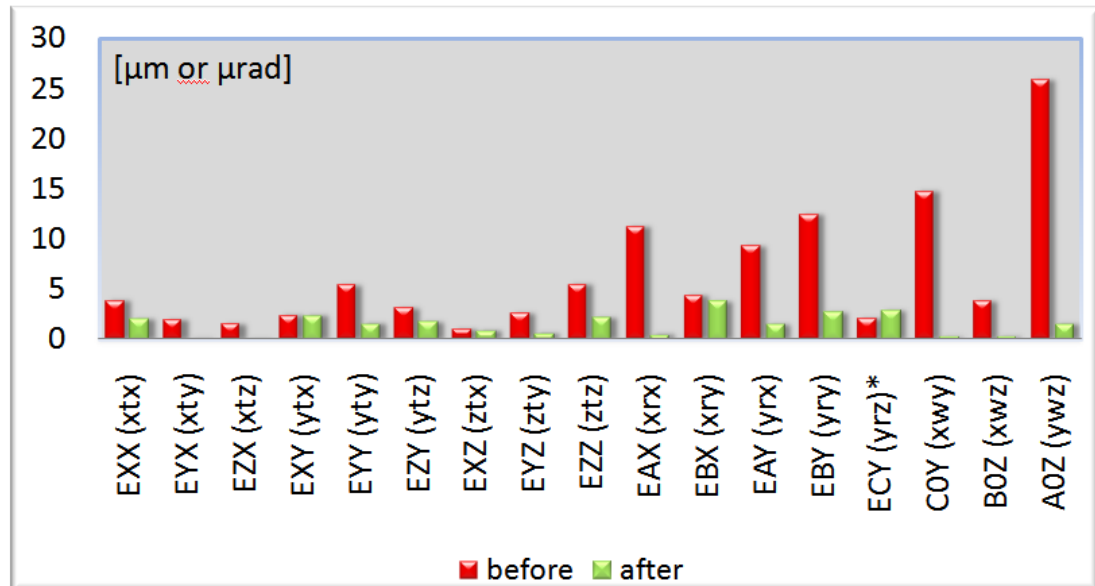
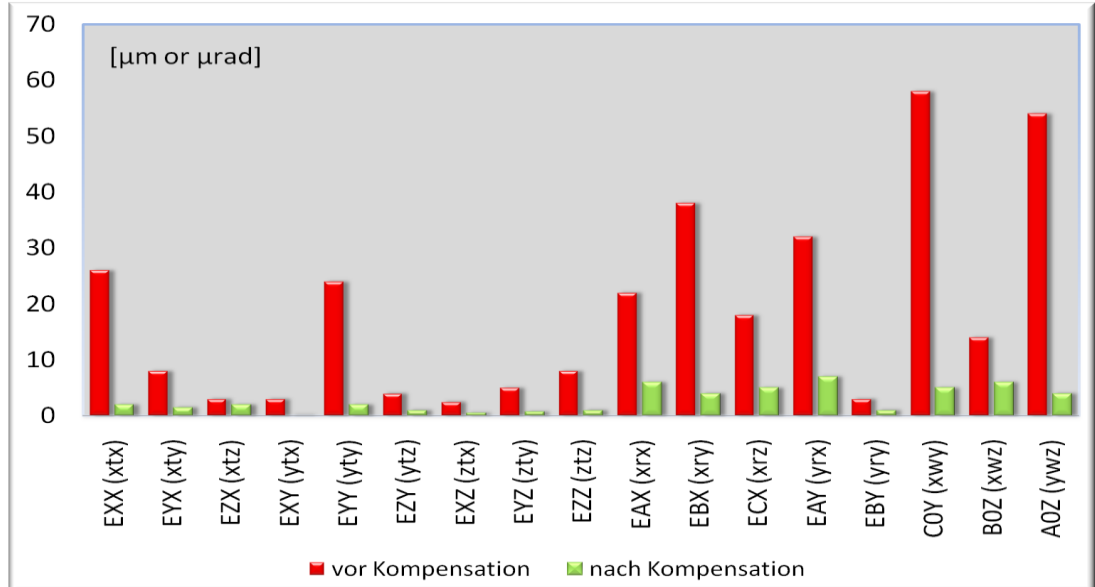
- ▶ **Siemens: “Volumetric Compensation System (VCS)”**  
Lookup tables for all kinematic parameters. Library of kinematic configurations.  
New: VCS rotary. Vector compensation for rotary axes.  
Pro: Easy to handle for user  
Con: Not all kinematic configurations covered
- ▶ **Fanuc: “3D-Compensation/3D rotary compensation”**  
Vector field stored in 3D-matrix. 3D rotary also stores rotation vectors  
Pro: General concept, no kinematic assumptions, easy installation  
Con: Limited number of sampling points
- ▶ **Heidenhain: “Kinematics Comp”**  
Configurable lookup tables for linear and rotary axes. Can be configured for arbitrary kinematic setups.  
Pro: Very flexible and general  
Con: Installation requires considerable Know-How
- ▶ **Mazak, Fidia, Fagor : Similar to Siemens VCS**

# Volumetric vector description of a Cartesian Machine





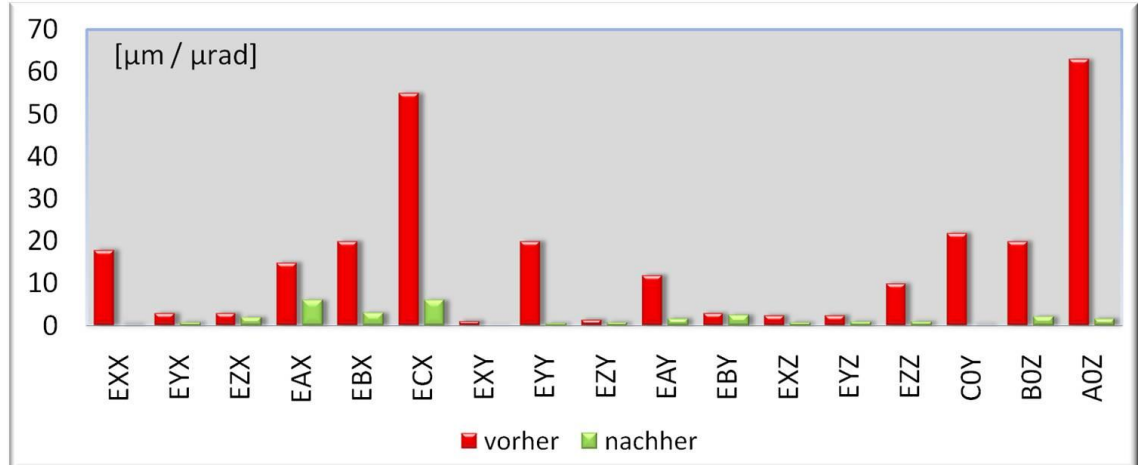
## Middleclass machining center with Fanuc control



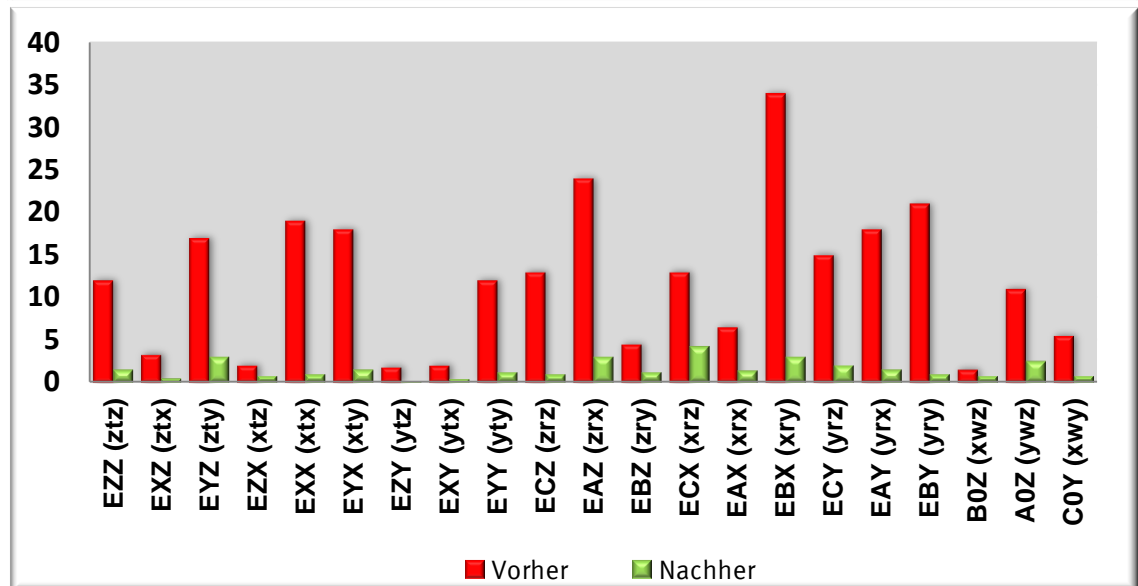
## High end machining center with Fanuc control

# Comparison before/after compensation with Siemens 840D

Vertical machining center

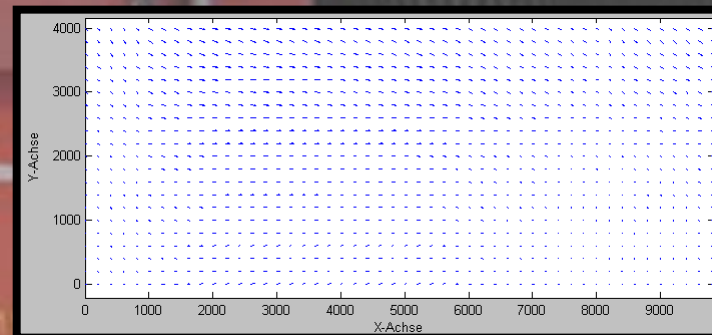
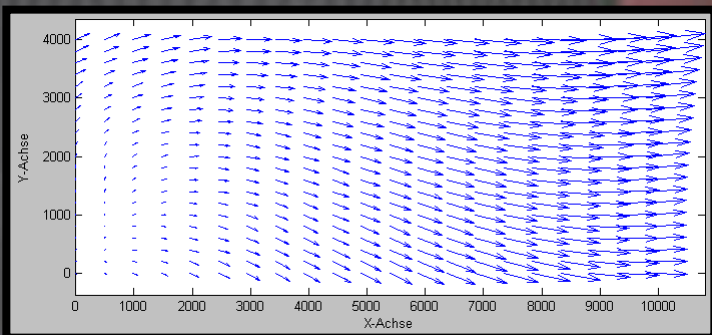


Horizontal-machining center

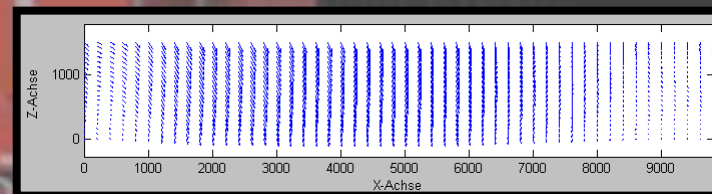
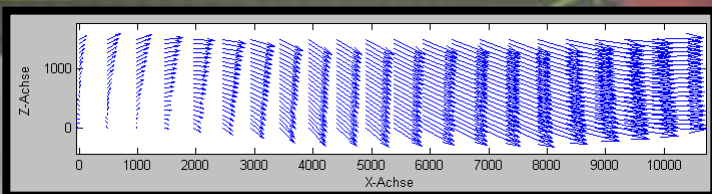


# Large Gantry machine with FIDIA control

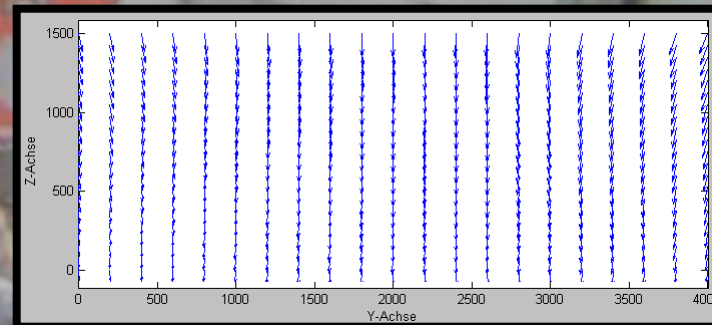
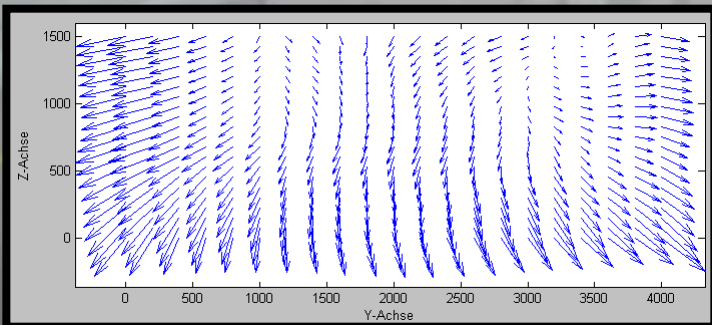
**XY**



**XZ**

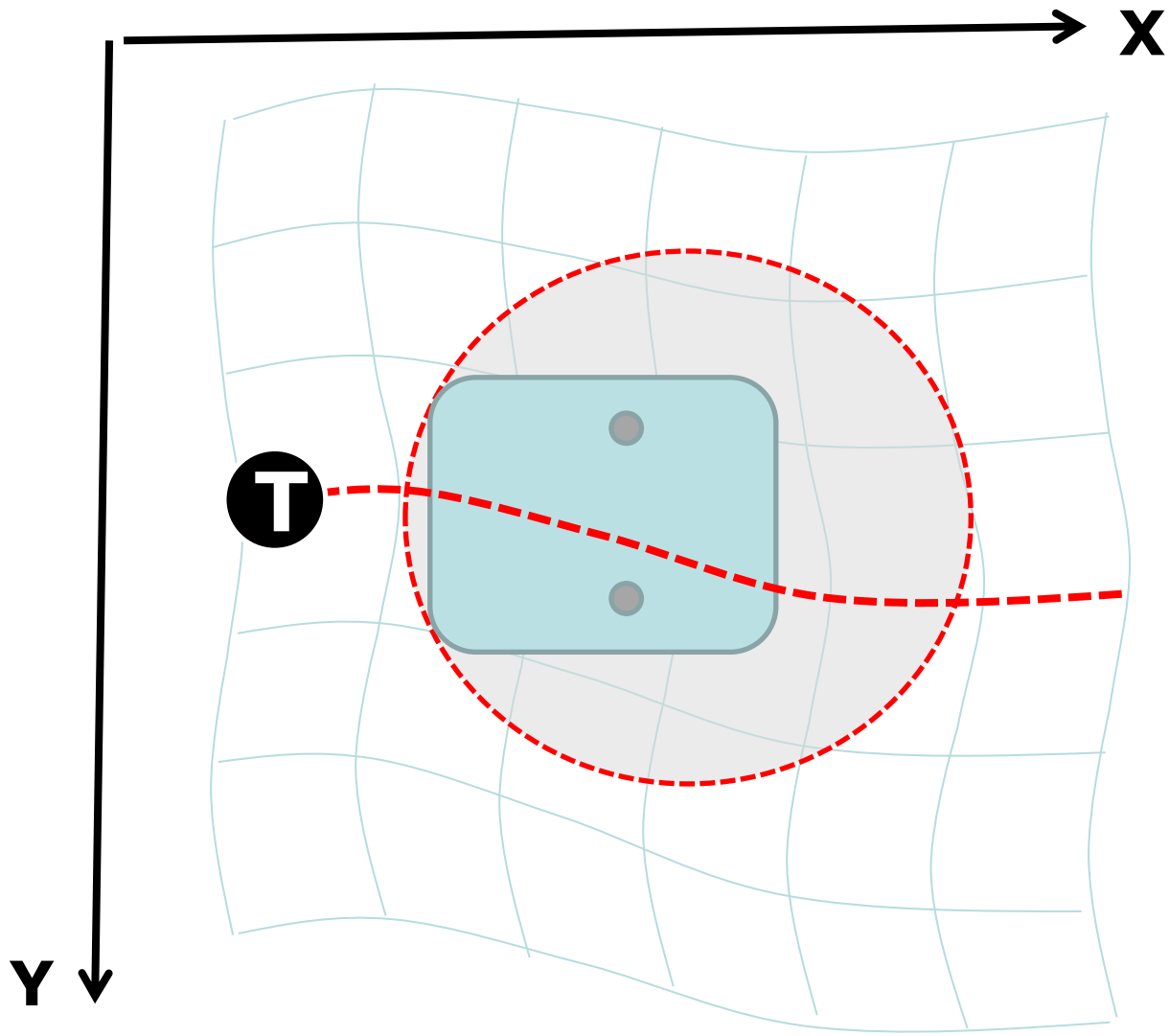


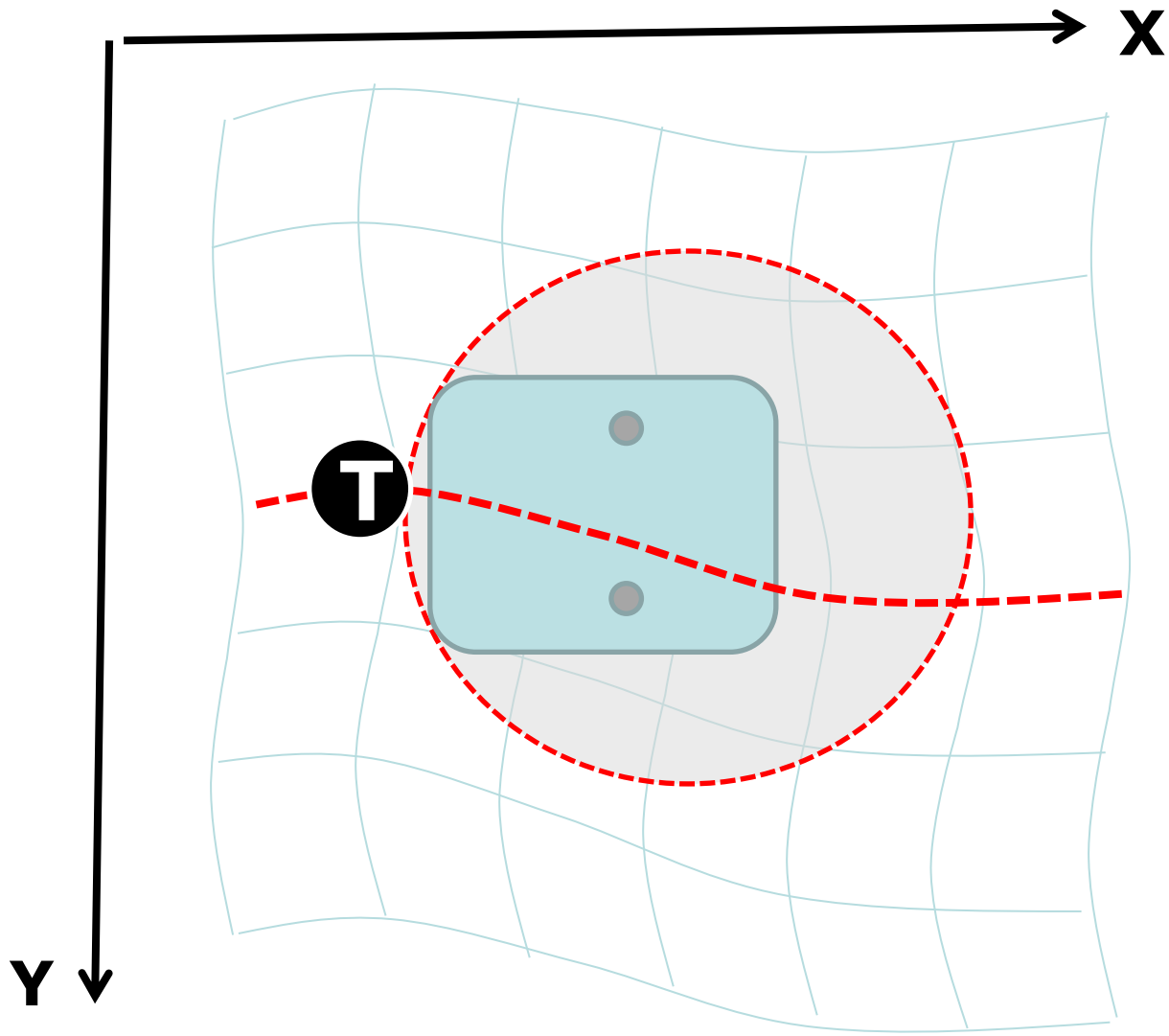
**YZ**

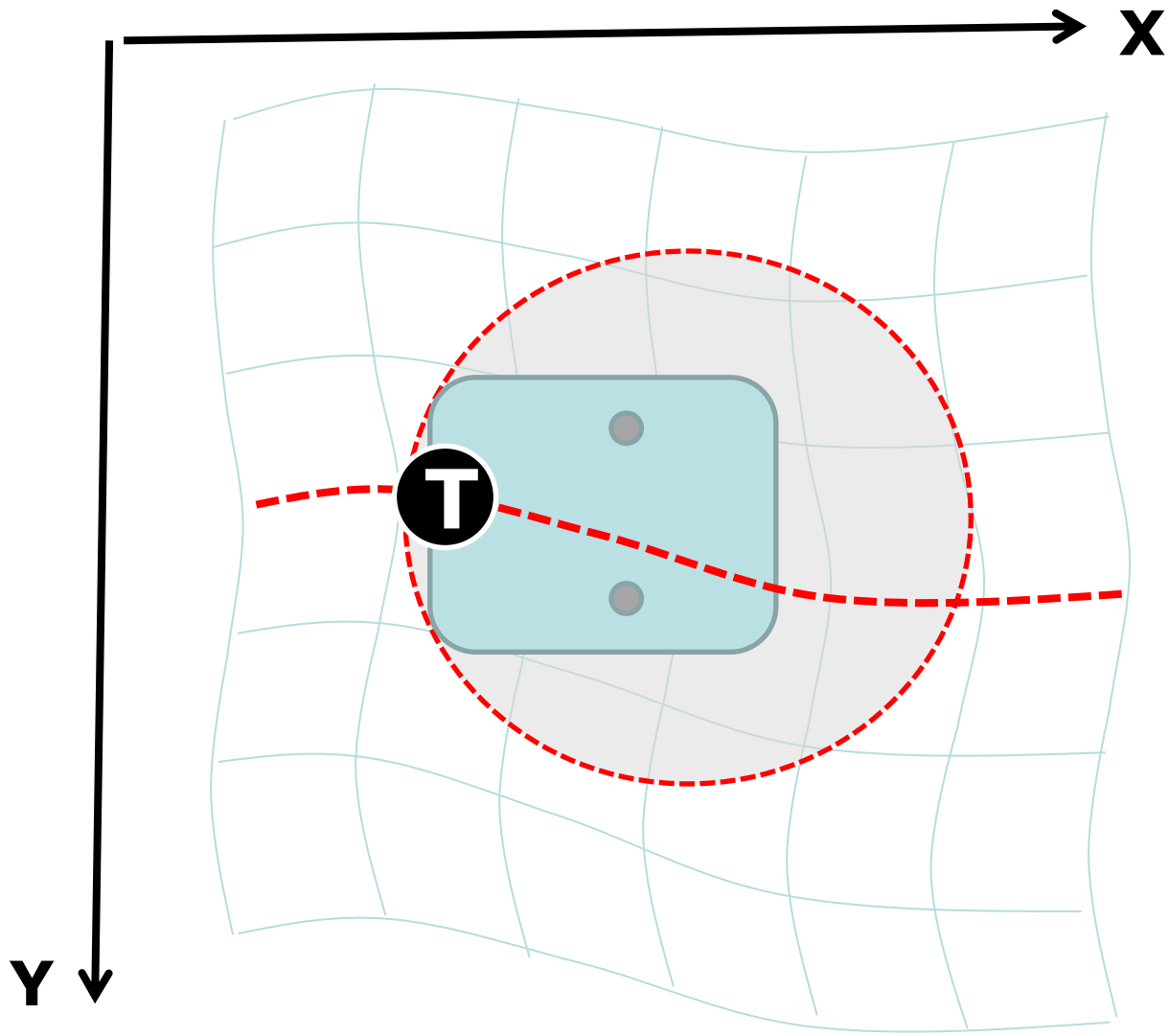


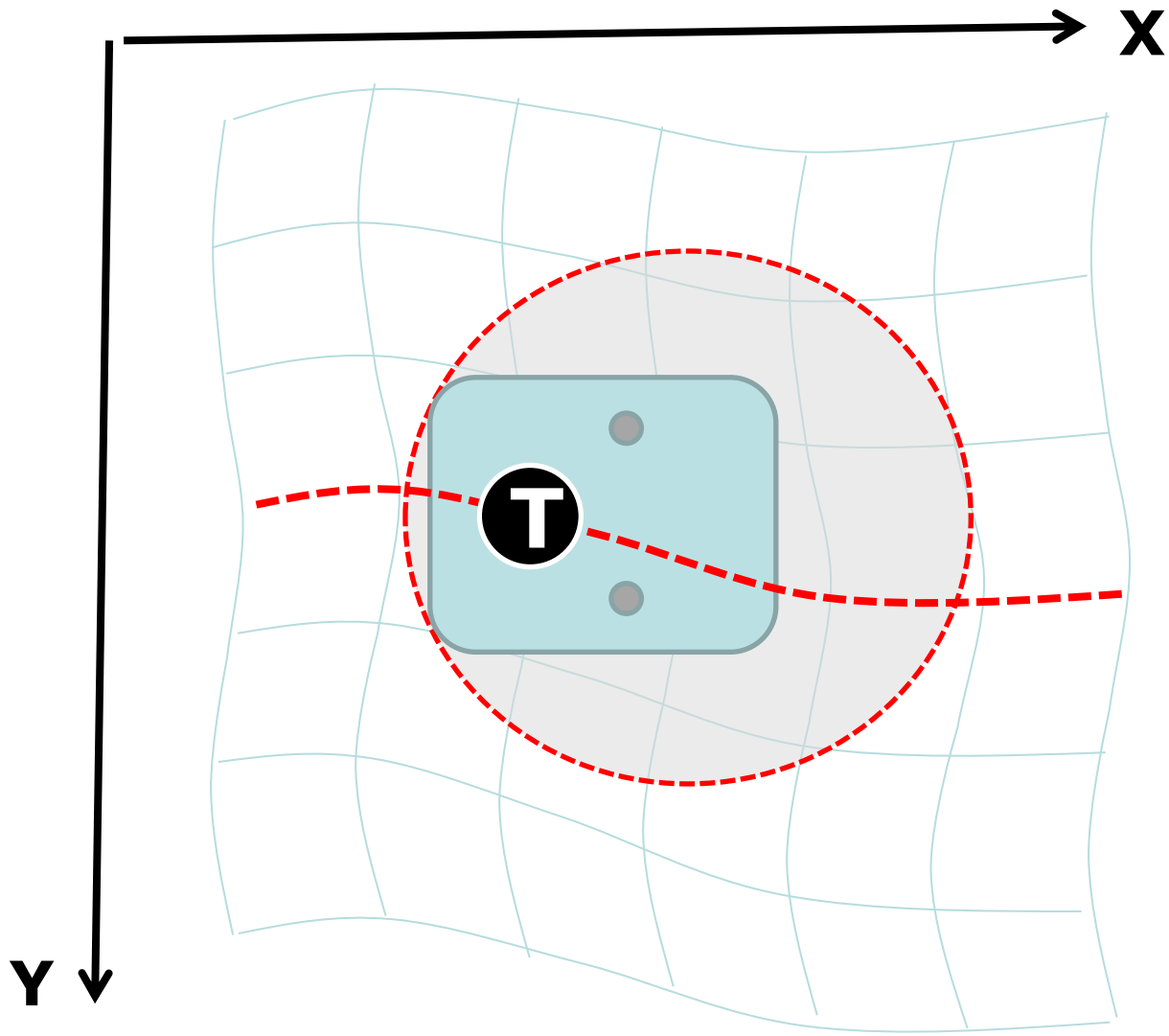
## Benefits of “Volumetric compensation”

- ▶ **Accuracy enhancement:** field experience has shown, that a typical accuracy gain by compensation is 60-80% (Reduction of observed length errors measuring in multiple directions across the volume).
- ▶ **Relaxation of tolerance for components and assembly:** Well established compensation procedures can relax accuracy requirement during the production to a certain degree (see slide limits)
- ▶ **Accuracy maintenance:** Over the live cycle of the machine, the accuracy can be reconstituted by calibration. This is a benefit for the customer and a after sales business for the manufacturer.
- ▶ **4/5 axis machining:** Redundant axes increase the accuracy requirements for all axes. Without compensation errors of linear axes appear amplified in the machining result.

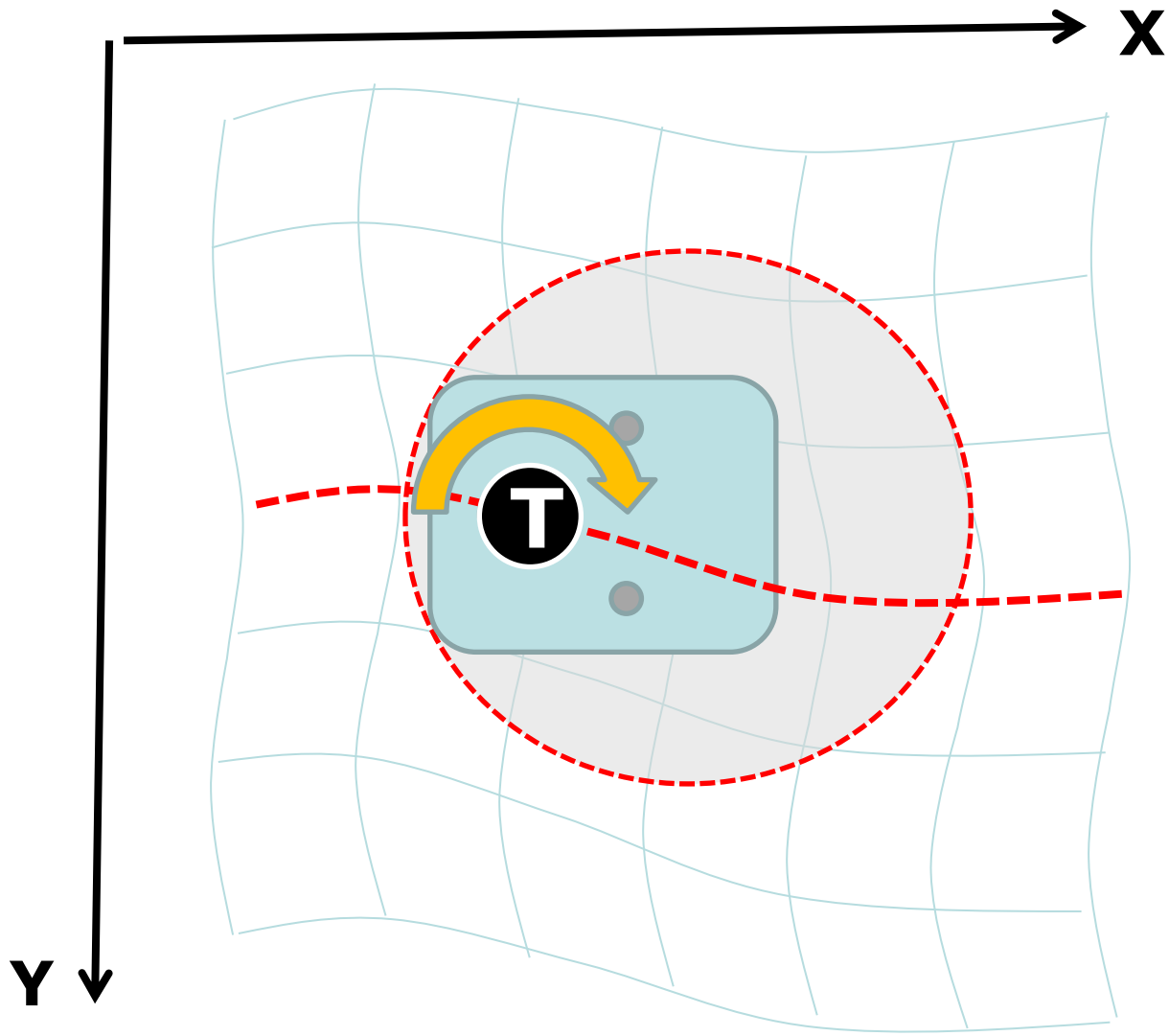


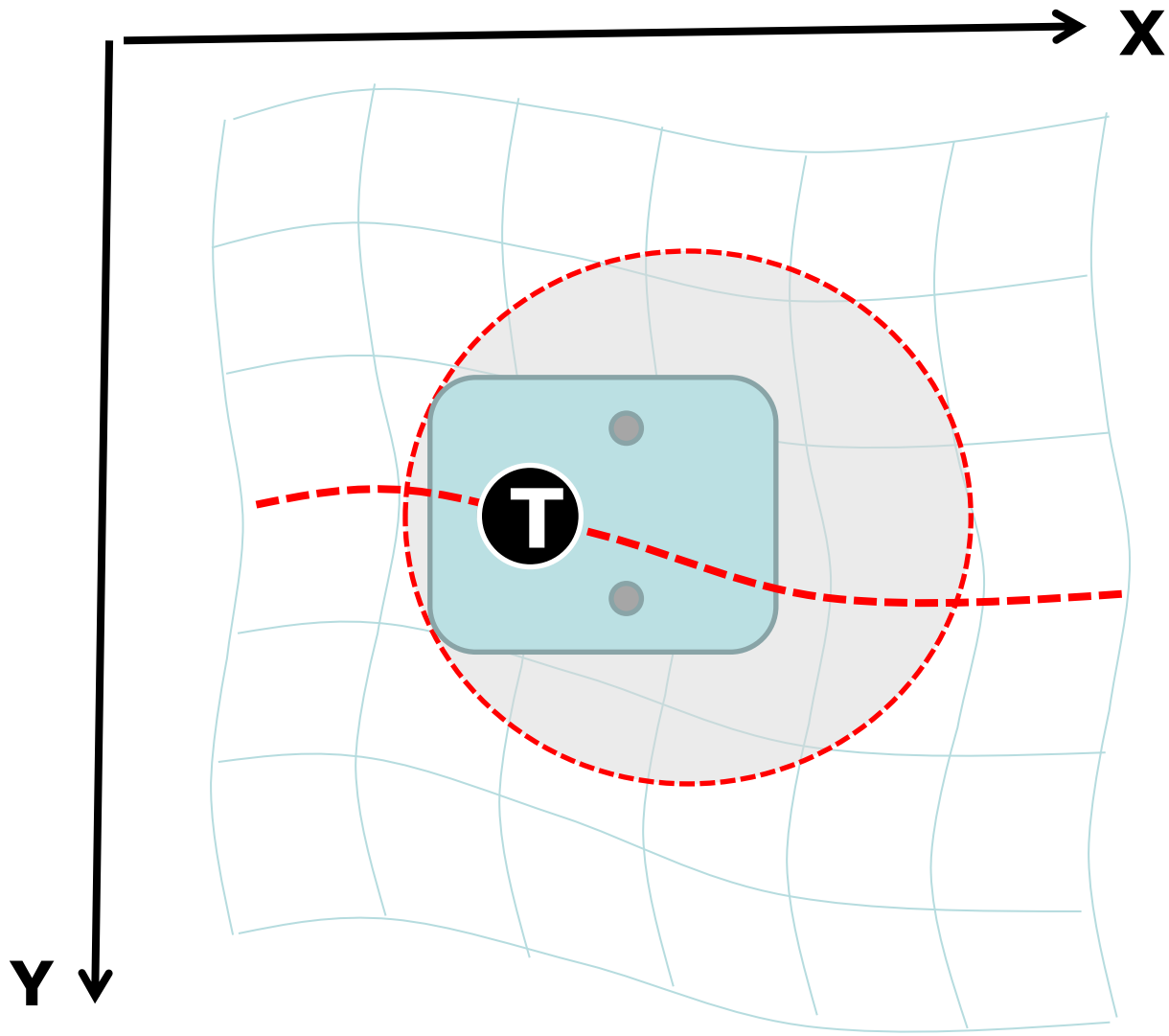


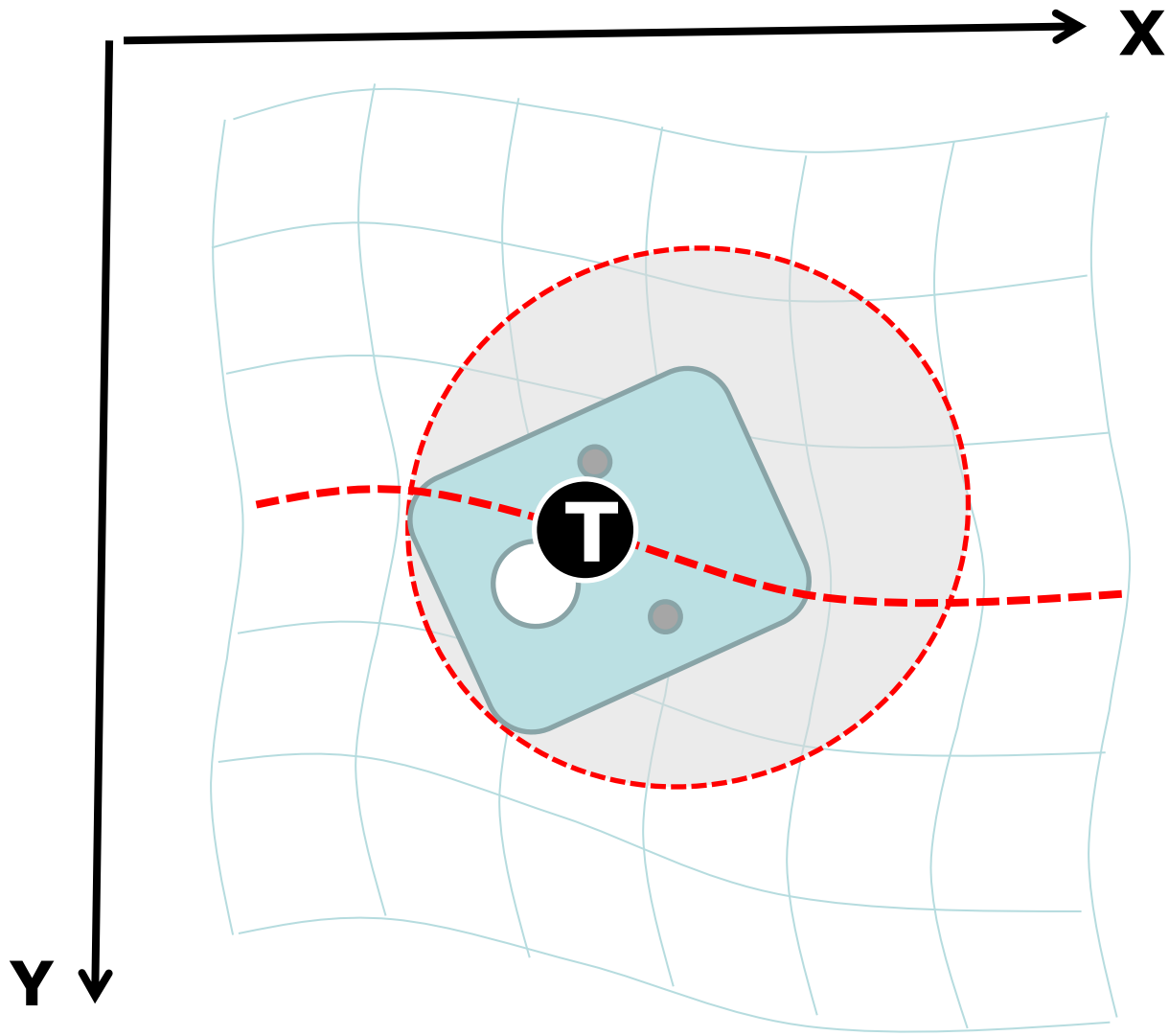


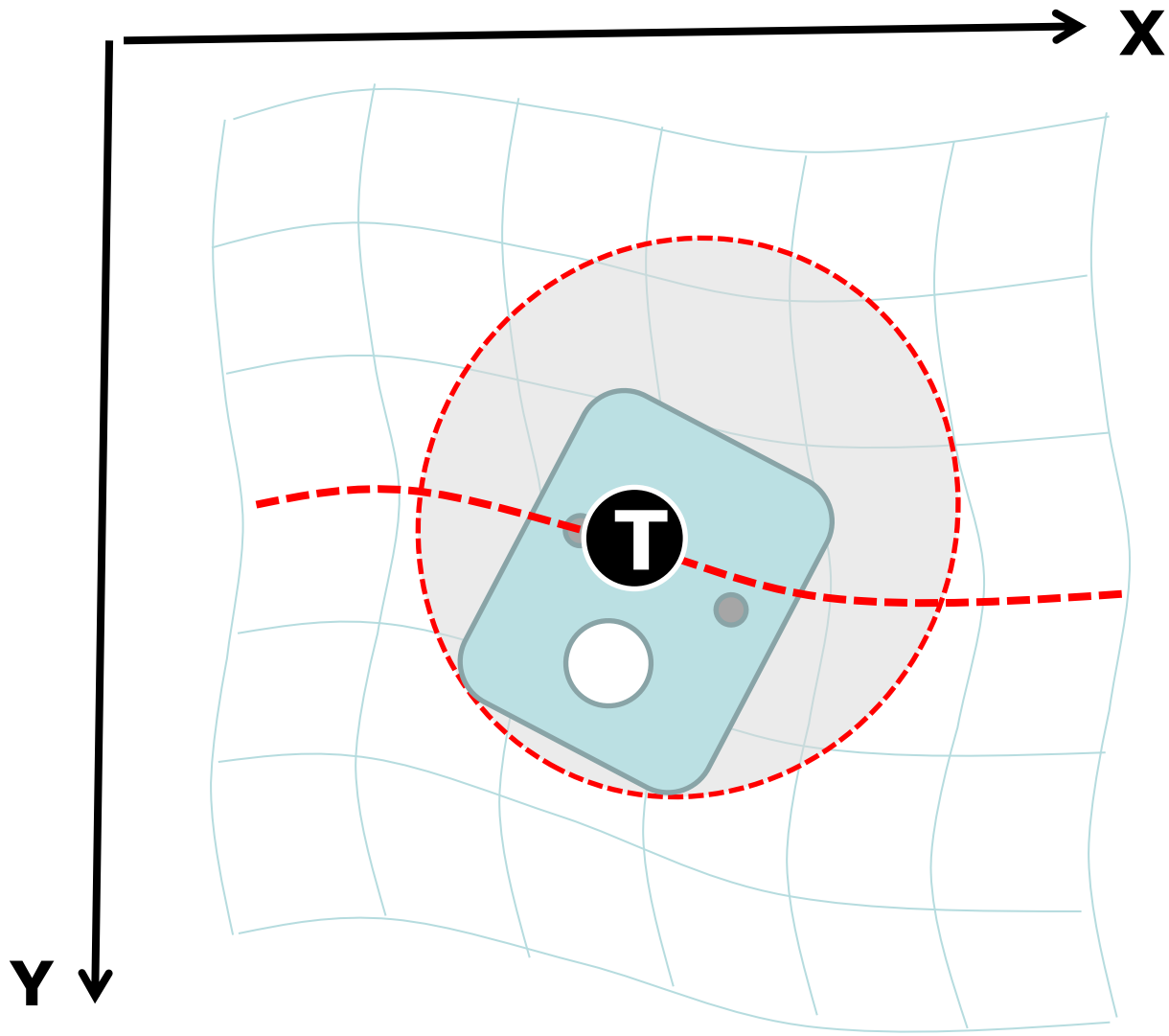


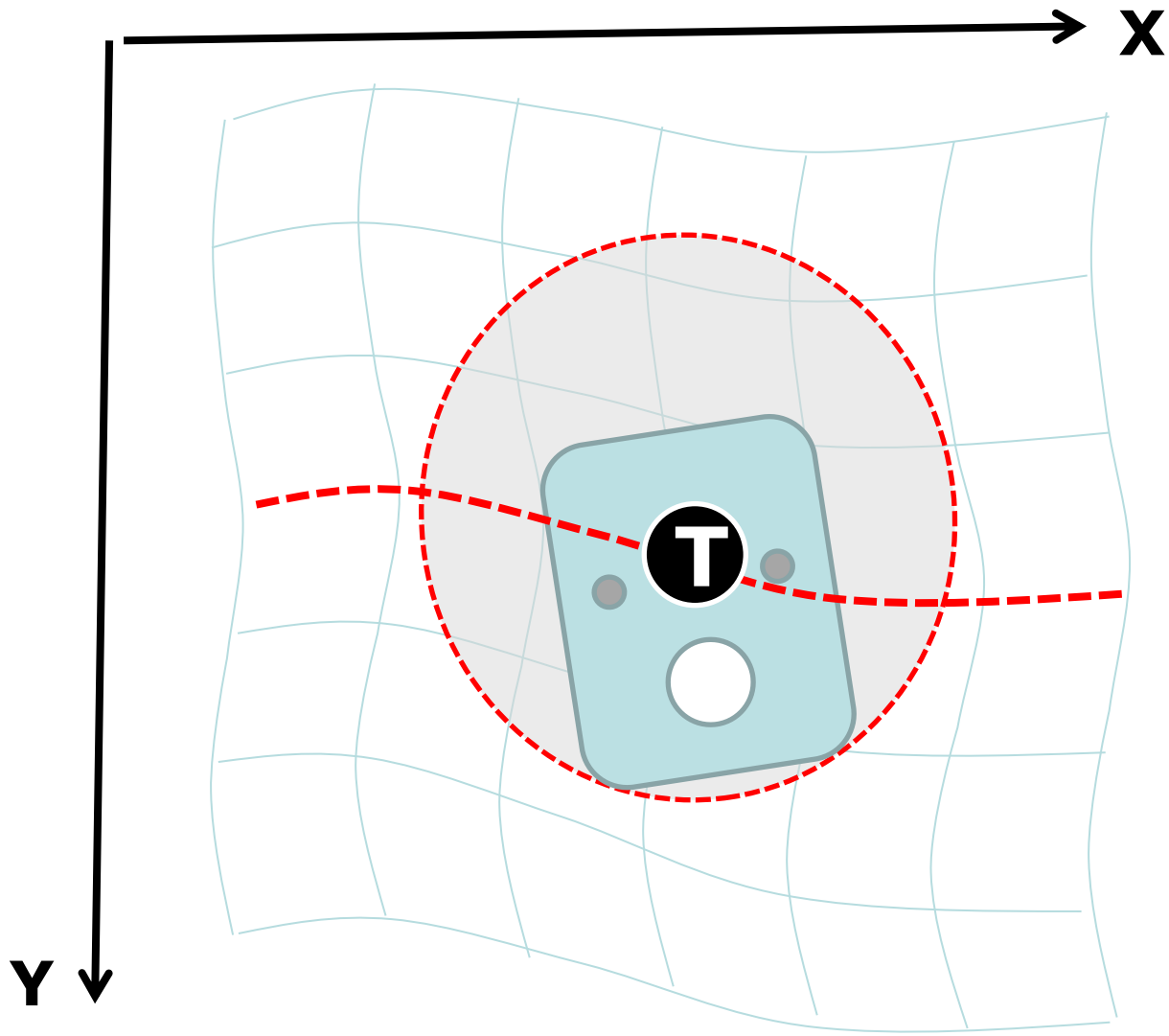


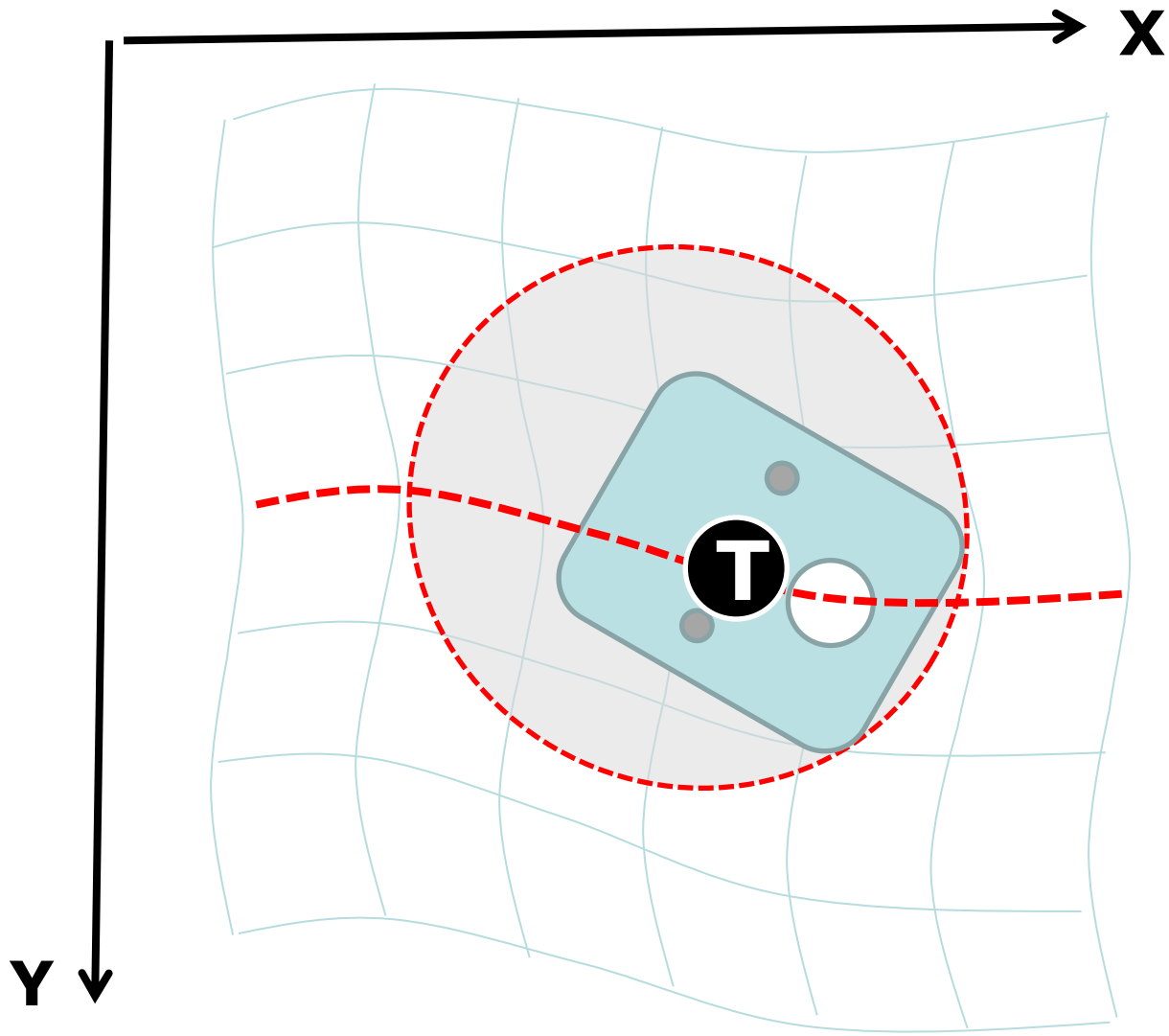


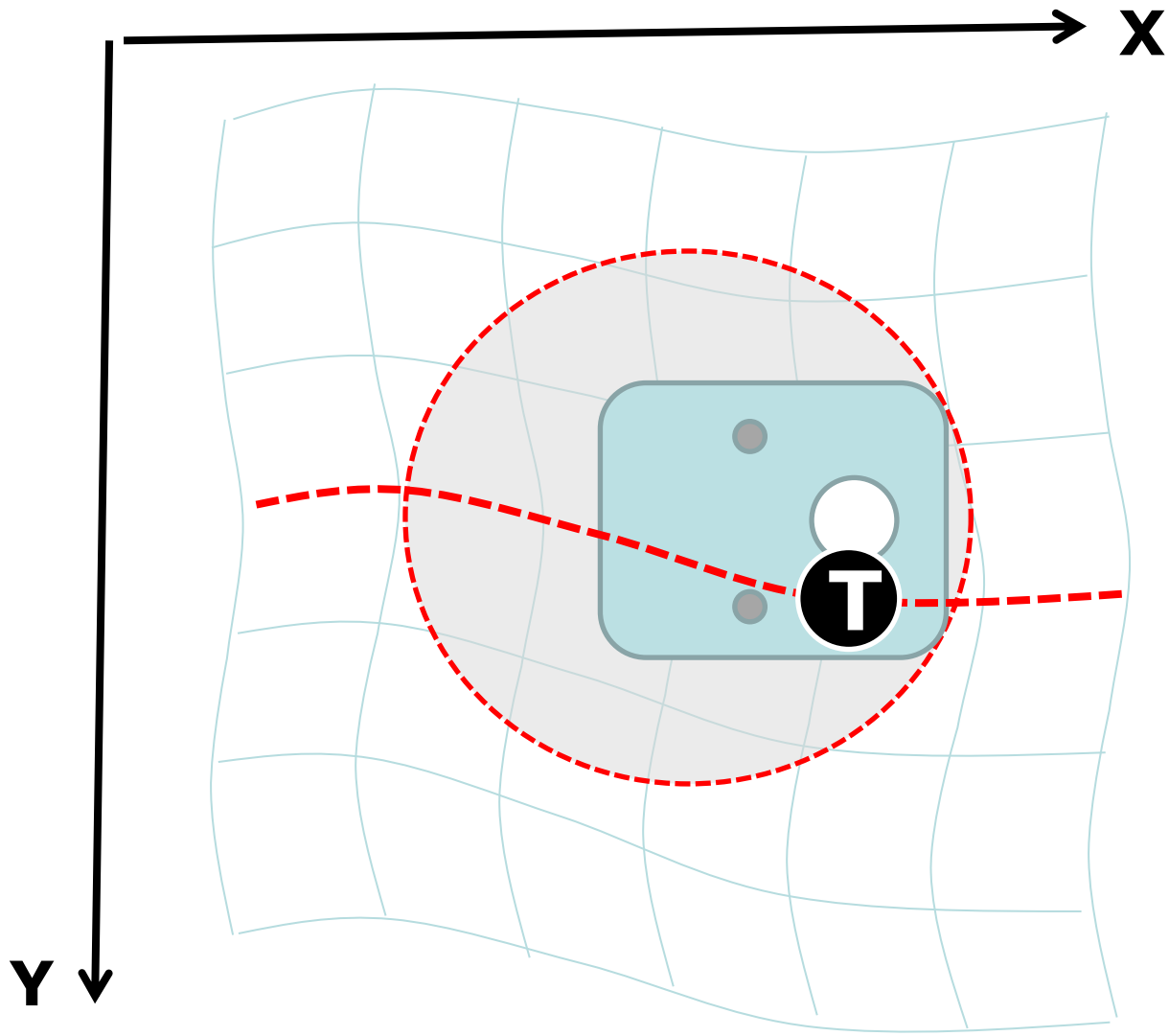




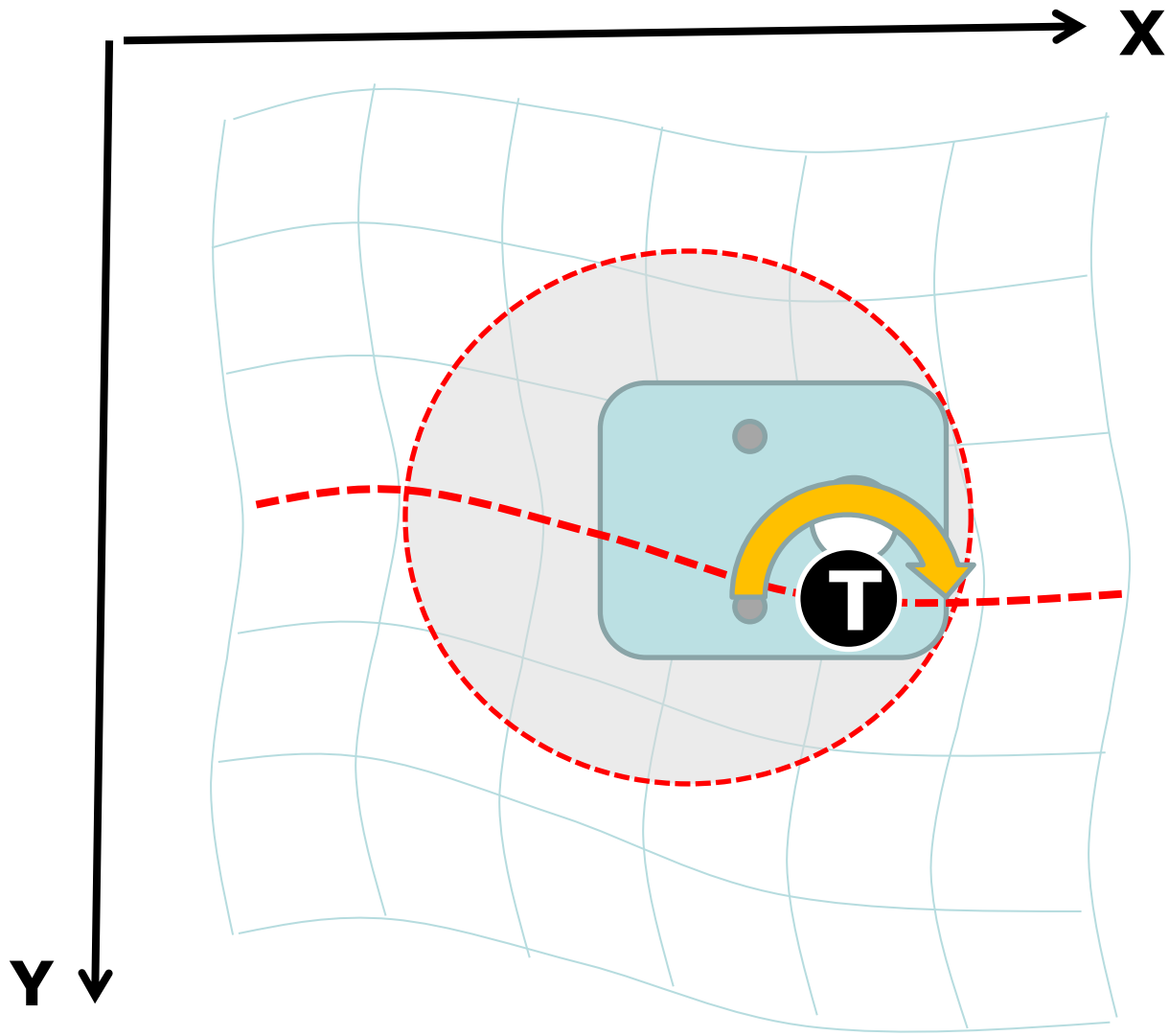


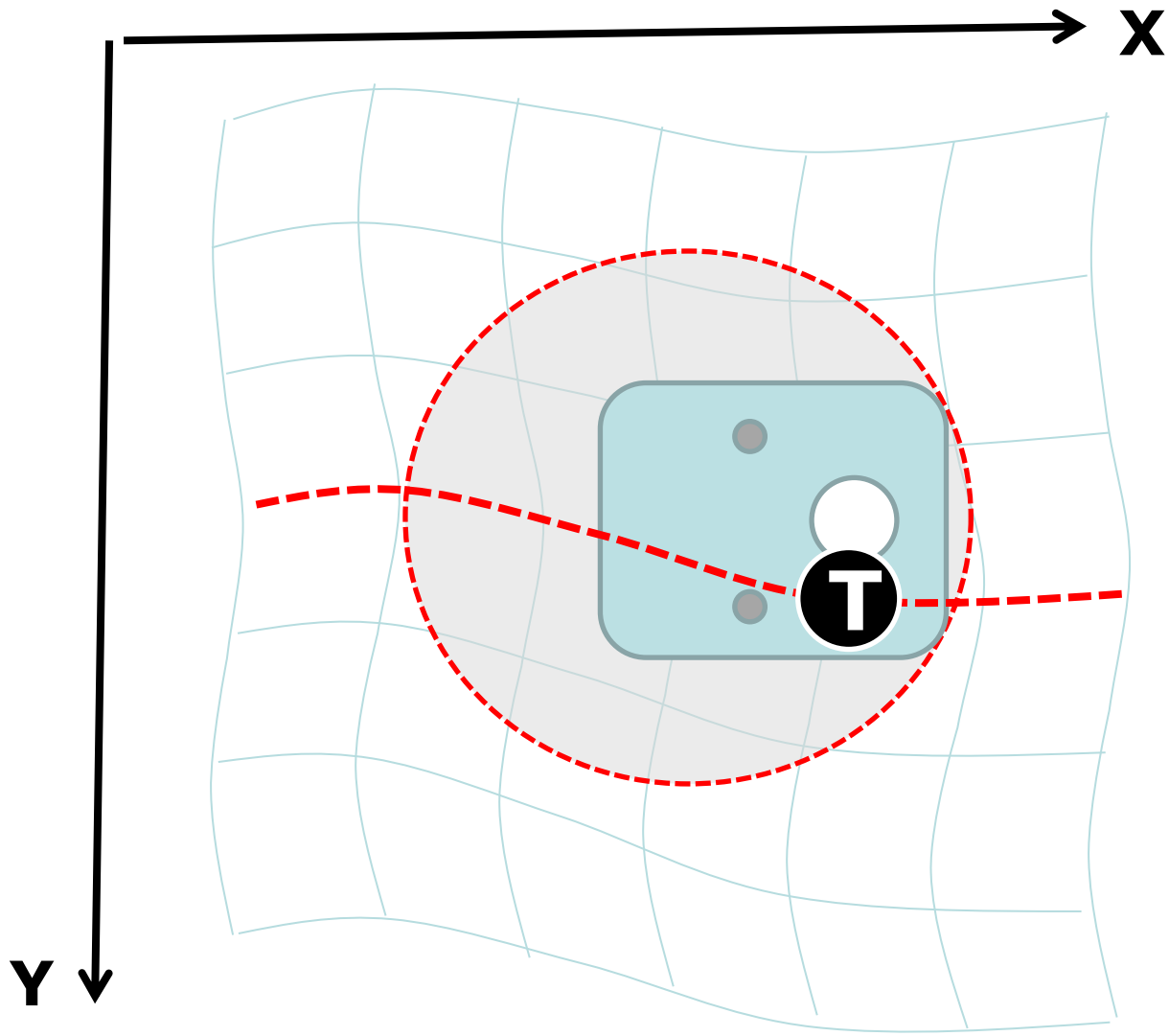


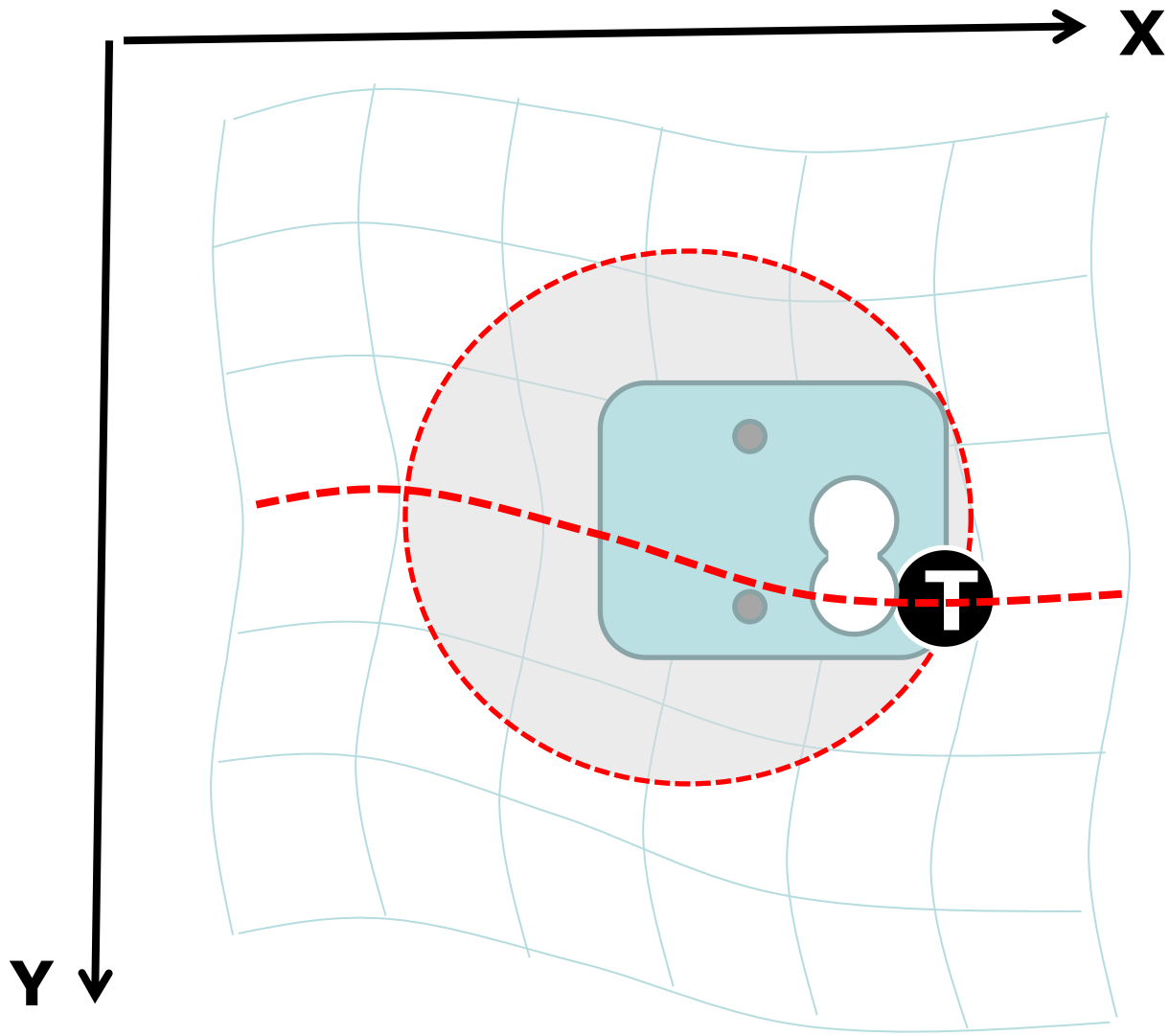


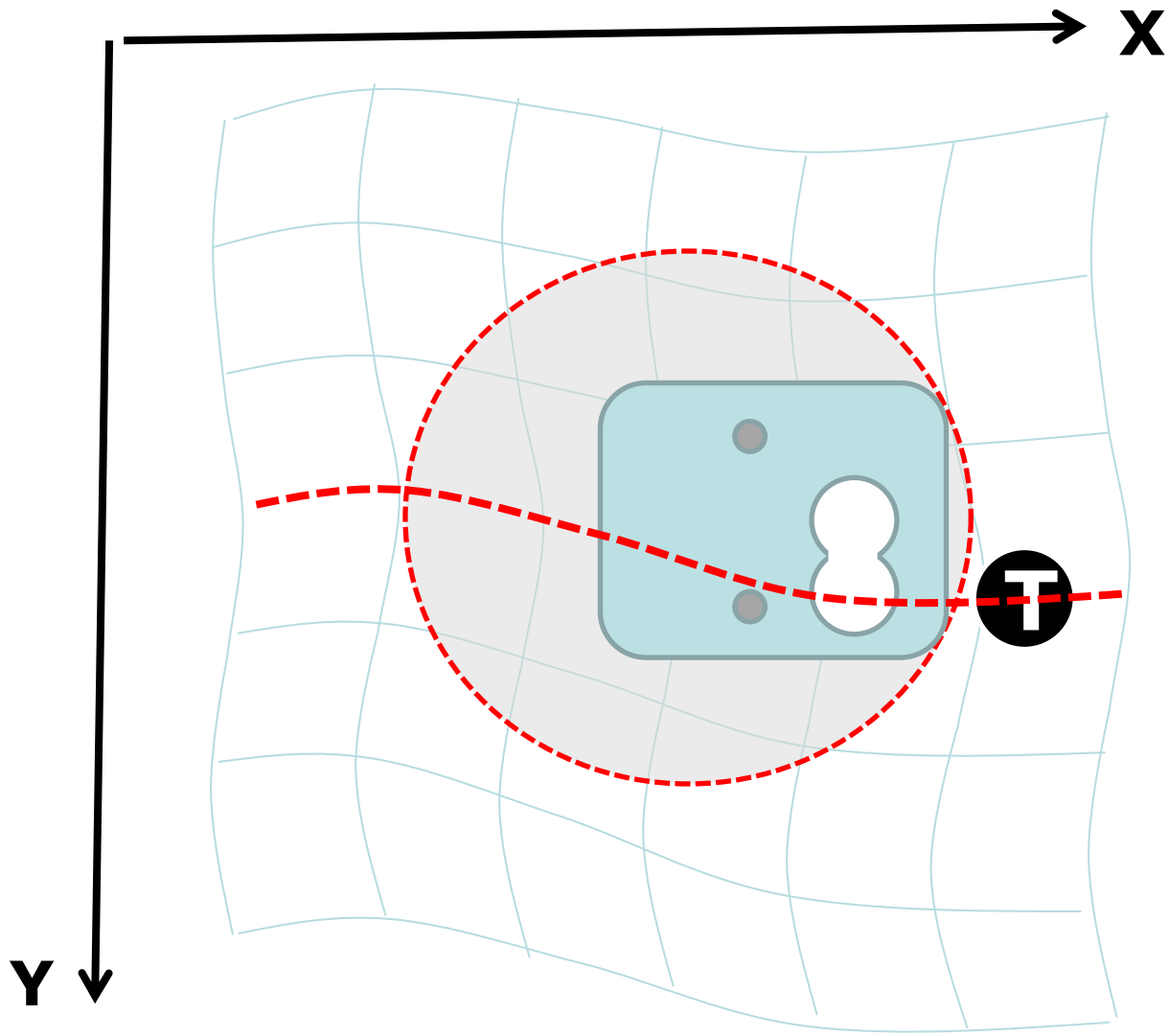












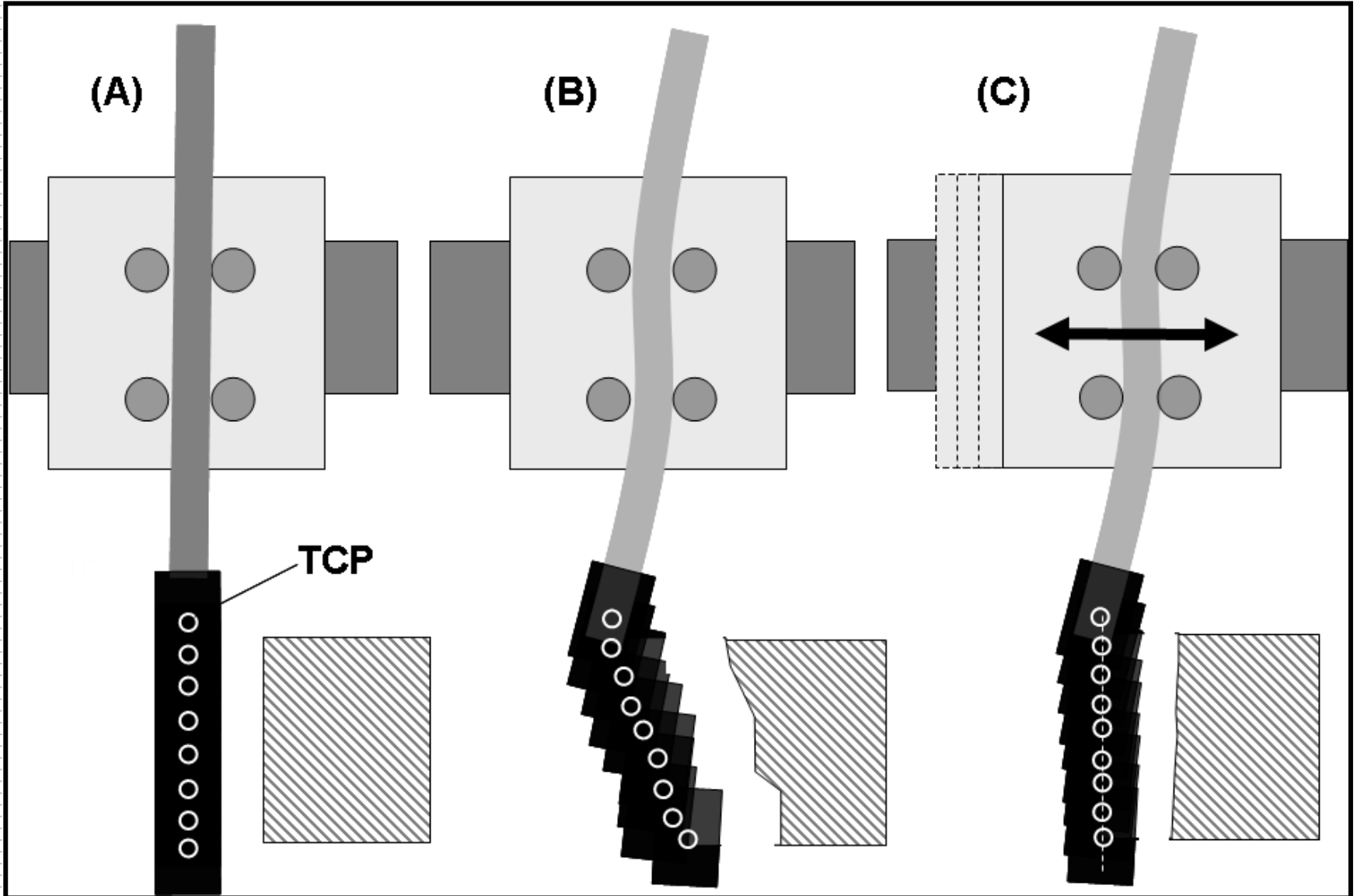
## Limits of volumetric compensation

- ▶ **Tool orientation:** on 3 axis machines, only position of tools centre point can be oriented.

Perfect machine

Real machine

TCP motion compensated



## Limits of volumetric compensation

- ▶ **Tool orientation:** on 3 axis machines, only position of tools centre point can be oriented.
- ▶ **Temperature variation:** ambient temperature gradients, thermal radiation and process energy cause machine structures to deform. Accurate machines need constant conditions or appropriate temperature models (compensated or not).
- ▶ **Model conformity:** Compensations require a conformity of the machine to the model assumed. It does not have to be the “rigid body model”, but extending the model parameter space increases the metrology effort. Example: Moving table torsion during X axis motion.
- ▶ **Hysteresis/backlash:** Modeling is challenging, due to multiple sources and complex behavior. In general, the backlash vector depends on the history of the motion of all axes. It can result from mechanical play in drives and guideways, cable track forces, stick/slip effects. It can be build up over  $\mu\text{m}$ , mm or m. It can effect position, straightness and (often!) pitch, yaw and roll.  
**But:** modern guideways and drives and direct position feedback have greatly reduced backlash problems.



## **Systematic characterization of possible thermal effects**

- ▶ Constant offset from the absolute reference temperature 20°C
- ▶ Slow changes over long time that result in a linear scale change of the entire machine
- ▶ Shorter frequency changes that do not affect the entire machine structure equally and therefore lead to bending and angular changes
- ▶ Change of spatial gradients (e.g. between foundation and factory roof), that also lead to geometry deformation of the machine structure

## **Most common ways to minimize thermal deformation of the machine structure are:**

- ▷ Warm up cycles of the spindle and the machine axes to reach a thermal equilibrium before machining (and calibration)
- ▷ Controlled cooling of drives and spindles and/or the machine structure
- ▷ Active control of the temperature of the cutting fluid and/or hydraulic oil
- ▷ Temperature controlled environment and avoidance of direct sun radiation
- ▷ Thermally symmetric design
- ▷ Passive damping of the machine structure
- ▷ Active temperature control of the machine foundation
- ▷ Optimization of material in regard to thermal expansion and conductivity.

## ISO machine tool standards for testing

- **ISO 230-1:** Gives a very good overview. In newest addition also introducing Etalons multilateration approach
- **ISO 230-2:** Established standard procedure for testing of machine tools axes
- **ISO 230-6 :** Extends axis parallel testing of ISO213-2 to diagonal testing. Very sensitive to volumetric errors.
- **ISO TR 16907: Numerical compensation of geometrical errors of machine tools:** New technical report on volumetric compensation is currently under preparation in the ISO committee.

## **ISO Technical Report 16907:**

### **Numerical compensation of machine tools**

- Introduces terminology
- Discusses advantages and limitations
- Introduces classification for compensations
- Helps MTBs, metrology people and users to communicate

**Now a working document in ISO, to be published end of 2013**

## How does workpiece accuracy profit from Volumetric Compensation?

### Case studies (1/2):

- A machine tool builder manufacturing 5 axes test parts on a medium size horizontal machining centre and improving accuracy of critical features up to 70%.
- A printing machine manufacturer that was able to manufacture the first part right with a volumetrically compensated machine while typically 1-3 iterations were necessary to meet the required tolerances.
- An automotive company that could prove by a number of test patterns on a large dies that the accuracy of the machining was improved considerably: The company decided that for all future machines a volumetric compensation option is a purchase requirement.

## How does workpiece accuracy profit from Volumetric Compensation?

### Case studies (2/2):

- A formula one team updating their 10 years old machining centres with volumetric compensation and could improve their part accuracy significantly.
- In an aerospace defence program it was decided after first experience with volumetric compensation that all worldwide machines that are involved in the manufacturing of structural parts have to be equipped with a volumetric compensation option.

## Conclusion 1/2

- Systematic geometry errors are one error source for the measurement and the manufacturing of parts.
- While full error mapping has been established for CMMs for 15 years, it is now successfully introduced most machine tool controller manufacturers.
- Additional requirements for numerical compensation for machine tools are: Real time compensation in path generation, consideration of physical orientation of the tool.

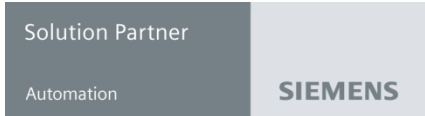


## Conclusion 2/2

- Increasing accuracy requirements, simpler mapping methods and the opportunity to decrease manufacturing costs of machine tools will promote the use of numerical compensation in the future.
- New international standards will promote the application of volumetric compensation, especially the diagonal testing of machine tools according to ISO 230-6 and the emerging TR 16907 on volumetric compensation.
- Knowledge on Volumetric Compensation in industry is constantly growing.
- Etalon estimates that in 2020 50% of all new machine tools will be compensated volumetrically.
- Volumetric mapping and re-mapping of machine tools will become a growing business for machine tool manufacturers and service providers.
- Etalon will work hard to maintain its role as a technology leader in this field

## Partners of ETALON

- ▶ Official partner companies for machine compensation



- ▶ Companies with cooperation for machine compensation



- ▶ System-partner for the testing of large machines



- ▶ Sales and service partner Japan



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