Sources of error and uncertainty in machine tool calibration

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University of Huddersfield

University of HUDDERSFIELD

- Founded in 1825
  - A history of education, innovation and industrial collaboration
- Over 2,800 staff
- 24,000 students
- studying more than 400 degrees
- An international University
  - Students from over 130 countries
  - Delivering courses in China, Hong Kong, India and Singapore

EPSRC Centre

- The EPSRC Centre for Innovative Manufacturing in Advanced Metrology
  - based at the University of Huddersfield's
  - Centre for Precision Technologies,
  - a long-established group with an international reputation in precision engineering and metrology research and development.

- Considering concept of the "***factory on the machine***", we require elevation of machine tool accuracies
  - hardware and software solution for stable metrology frame
  - Efficient, traceable calibration

Machine tool error measurement

Established

- Artefacts/ self-centring probes
- Laser interferometry
- …

Current SoA

- High accuracy laser trackers
- Sequential multilateration (TracCAL)
- Multi DoF lasers
- Ultra stable artefacts with scanning/optical probes

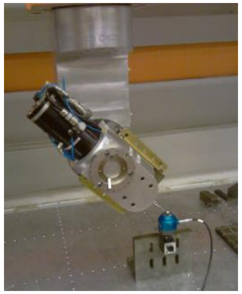
Future

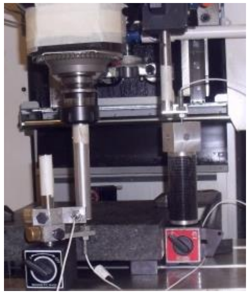
- Synchronised dynamic capture
- Affordable simultaneous multilateration
- Direct position feedback
- Continuous traceable adaptation

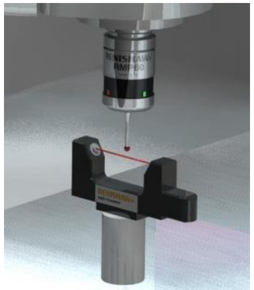
Faster — Greater accuracy — Volumetric

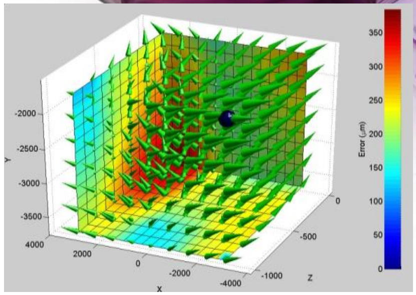
Subject of research work

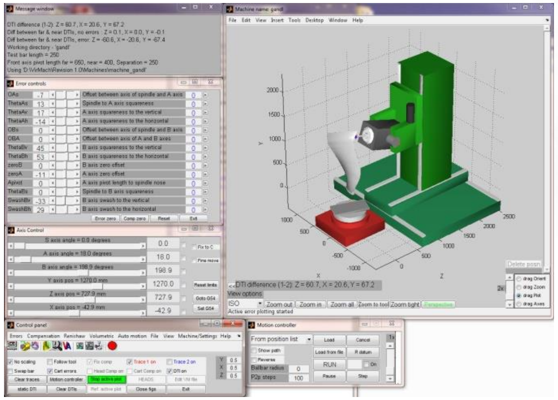
Machine tool measurement





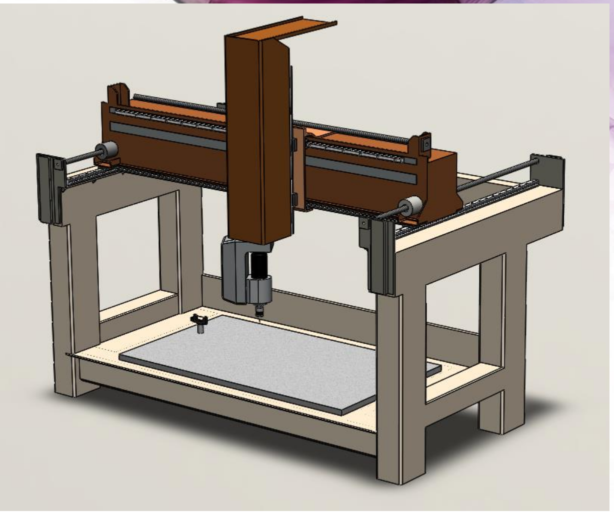


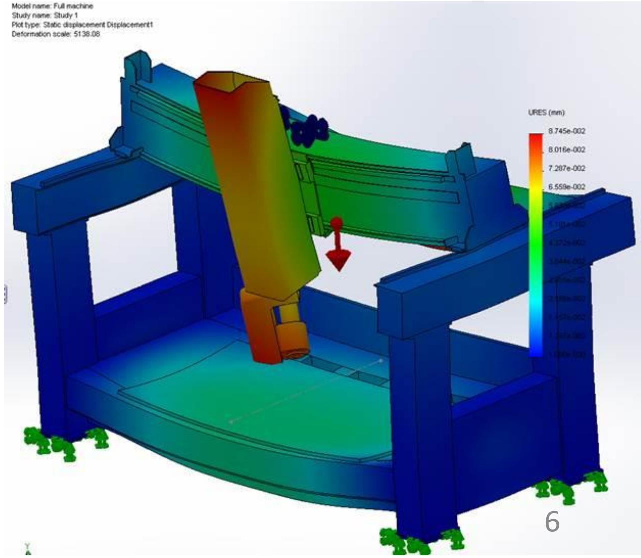




Main sources of uncertainty

- Some significant sources of uncertainty
  - Measurement methods
  - Comprehensiveness of data
    - Measurement of all error sources
    - Spatial resolution
  - Finite stiffness
  - Thermal deformation
  - Errors due to motion
  - Numerical compensation





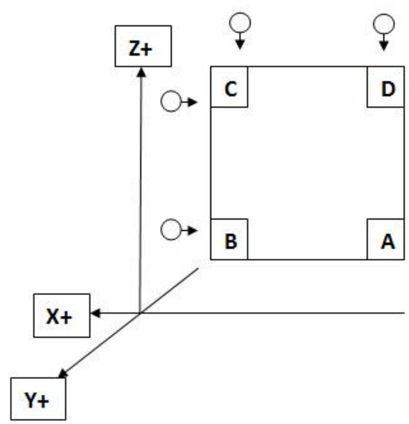
Measurement methods

International Standards

- ISO 230 Test code for machine tools
  - Part 1: Geometric accuracy of machines operating under no-load or quasi- static conditions
  - Part 2: Determination of accuracy and repeatability of positioning numerically controlled axes
  - Part 3: Determination of thermal effects
  - Part 7: Geometric accuracy of axes of rotation
  - Part 10: Determination of the measuring performance of a machine tool
- ISO 10791 Test conditions for machining centres

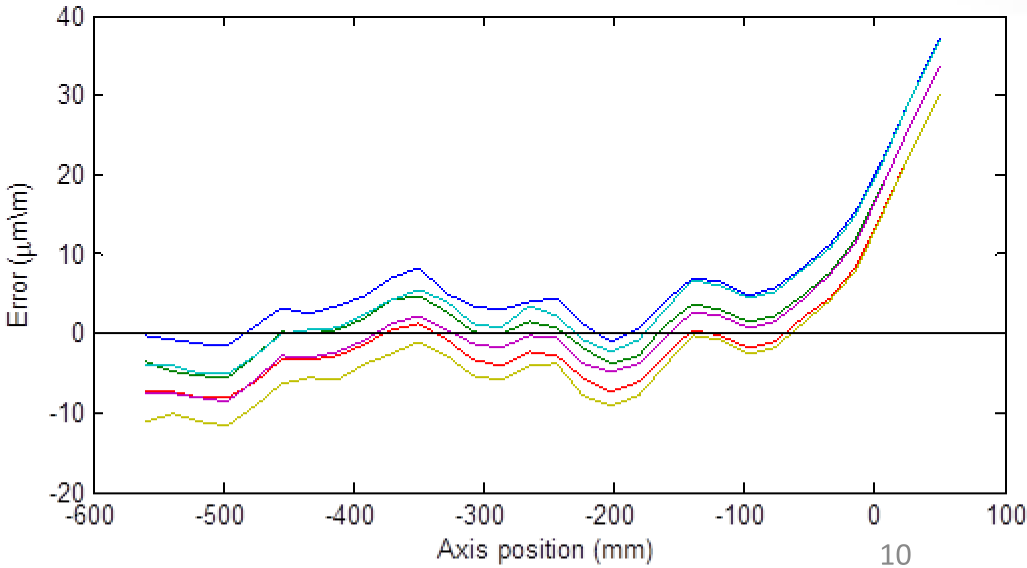
Fastest methods can increase uncertainty

- For example measurement of non-orthogonality between axes
  - Using a “squareness artefact”
  - Should be measured using two straightness measurements and least-squares fit
  - Often measured with four points on a square.



Equipment effects

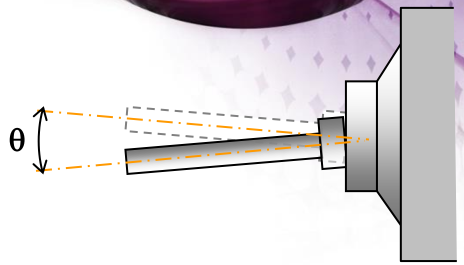
- Environmental factors and operator handling can induce thermal effects in instrumentation.
- In particular, angular and straightness interferometry is susceptible to
  - thermal and
  - mechanical stresses in the optics
  - due to the sensitivity of the measurement to beam separation.
- Production constraints often mean that equipment is not given sufficient time to stabilise
  - Without repeat measurement runs the drift would not be detected.

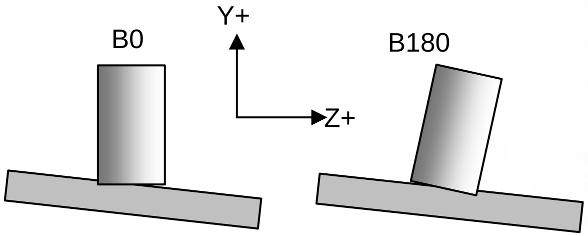


Comprehensiveness of data

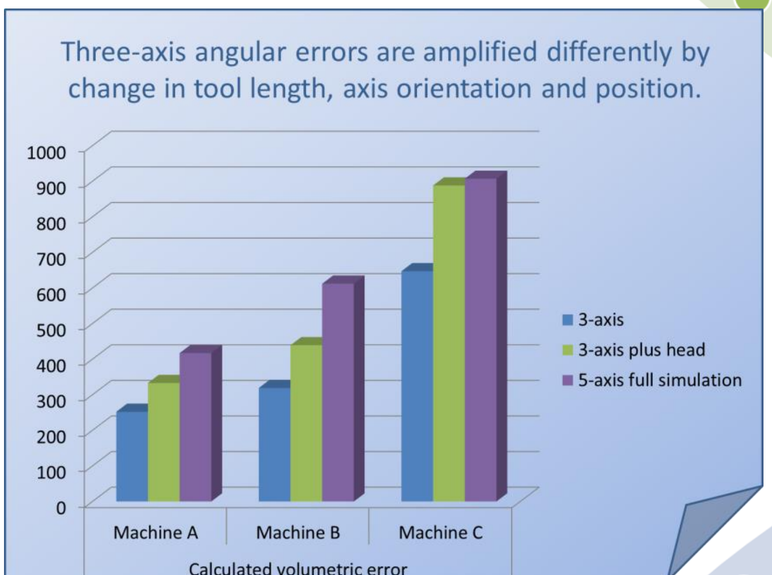
Geometric error sources

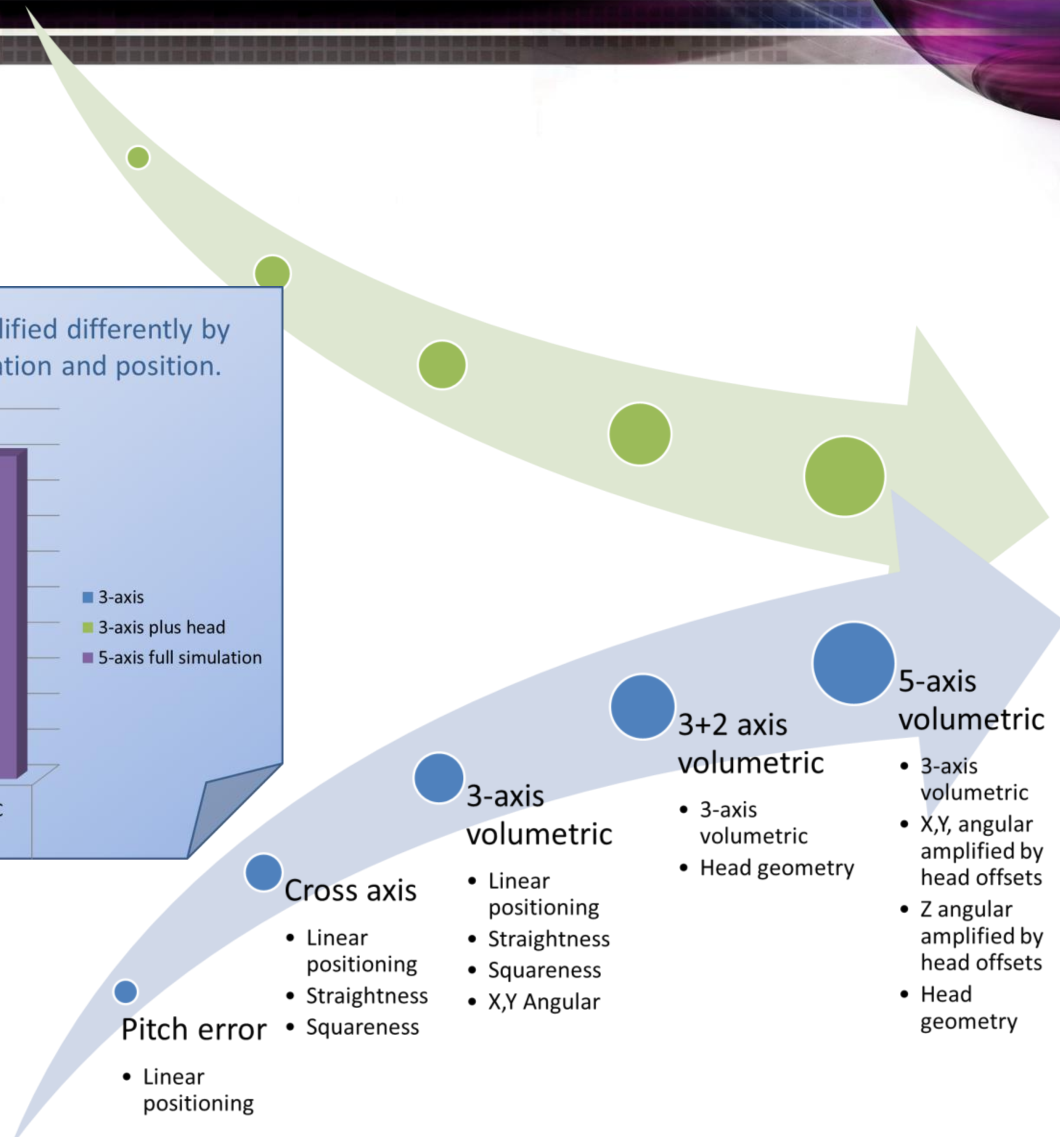
- On a three-axis Cartesian machine there are the traditional “21” sources of geometric error
  - Some sources are simpler to measure than others
  - Some have such high measurement uncertainty that they are ignored
- On machines with parallel or rotary axes, the number of error sources increases
  - Neglecting to measure all sources introduces uncontrolled uncertainty





Volumetric assessment





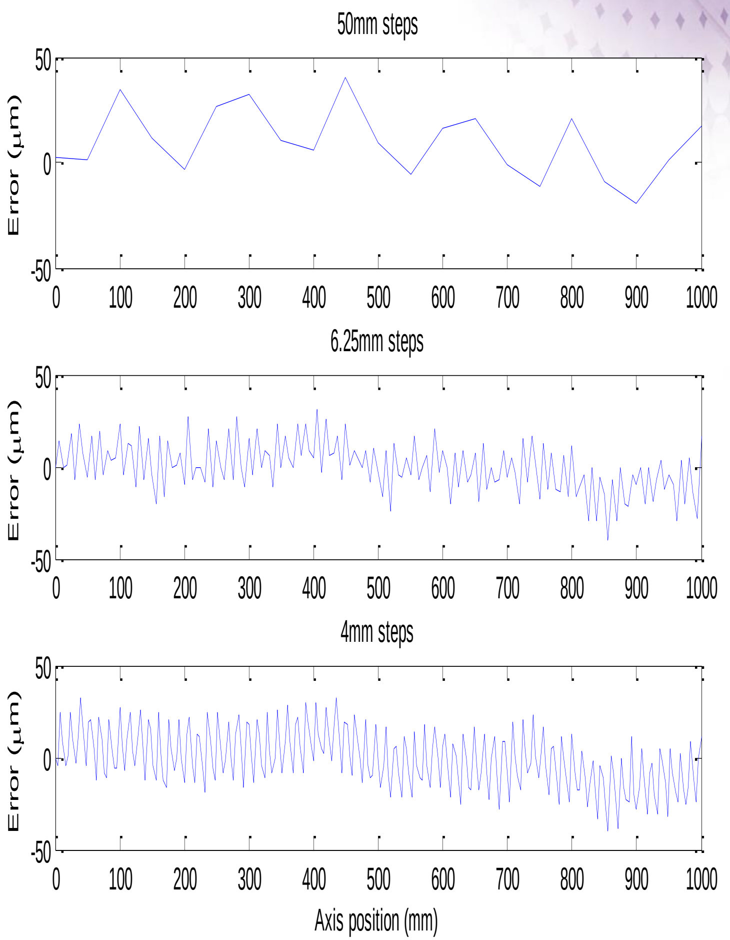
Decreasing omission of errors?

or

Increasing estimated uncertainty?

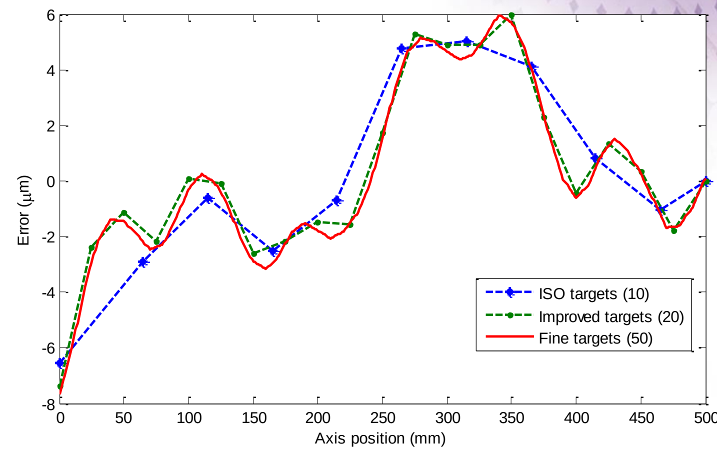
Spatial resolution

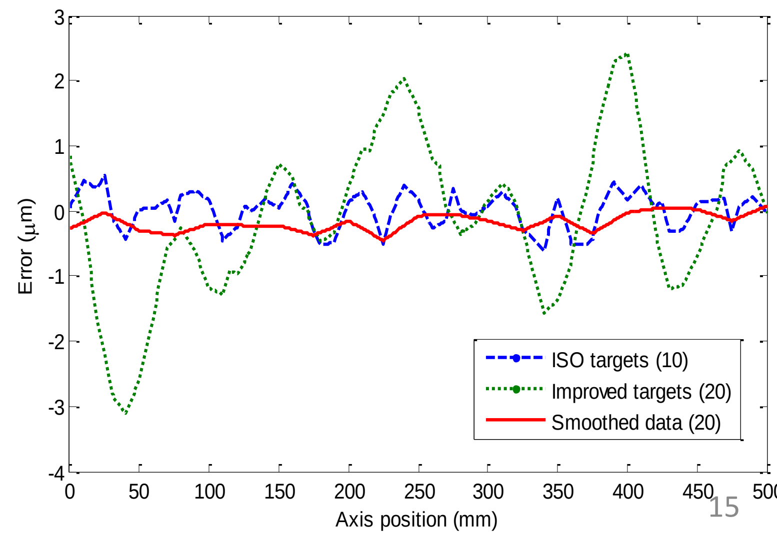
- Standard resolution measurement of vertical straightness
  - shows some cyclic behaviour but
  - may be mistaken as "noise"
  - not obvious as a ballscrew issue
- Sparse data therefore increases uncertainty
  - However length of test is increased by higher resolution



Spatial resolution

- Example 0.5m machine axis
  - ISO targets efficient
  - For axes up to 2000 mm, a minimum of five targets per 1000 mm and not less than 5 targets is required by ISO
- Error compensation applied on the machine using 10,20 and 50 targets
- Residual errors can be significant
  - Surface finish and form
- In reality the minimum is typically used
  - An effective option is filtering





Reducing error through filtering

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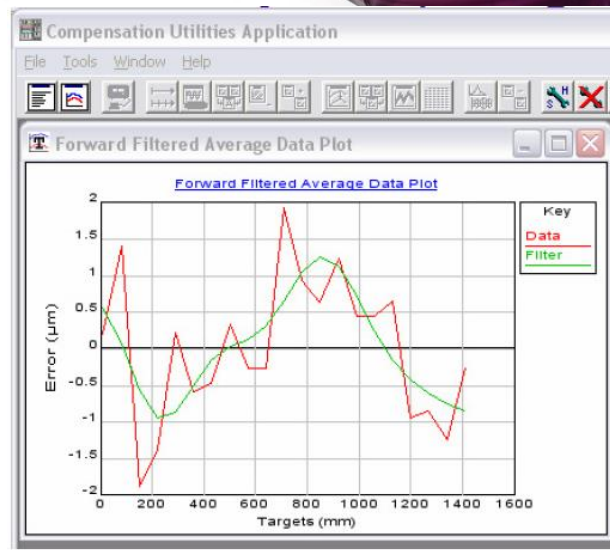
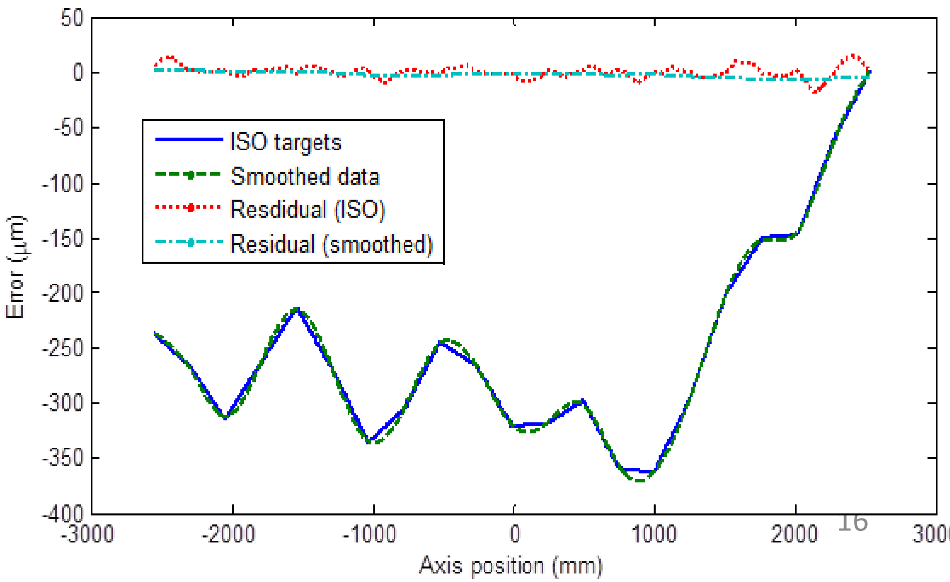
- The carriages/feet of an axis act as filters for high frequency imperfections
- Mathematical filters can
  - better approximate this effect
  - Improve noisy data from, for example, long range straightness data affected by air turbulence
- Technique also successfully applied to straightness error compensation
- However
  - Over-filtering may omit real imperfections

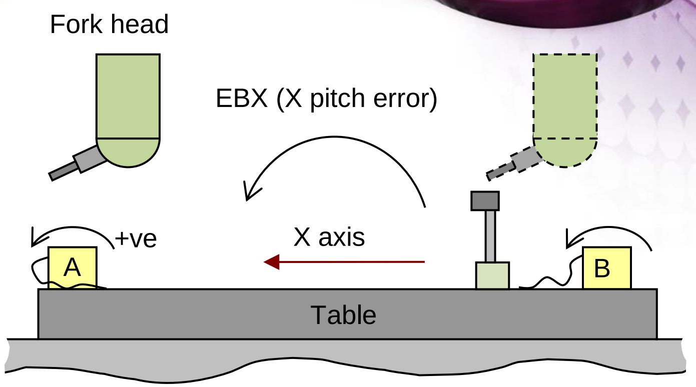


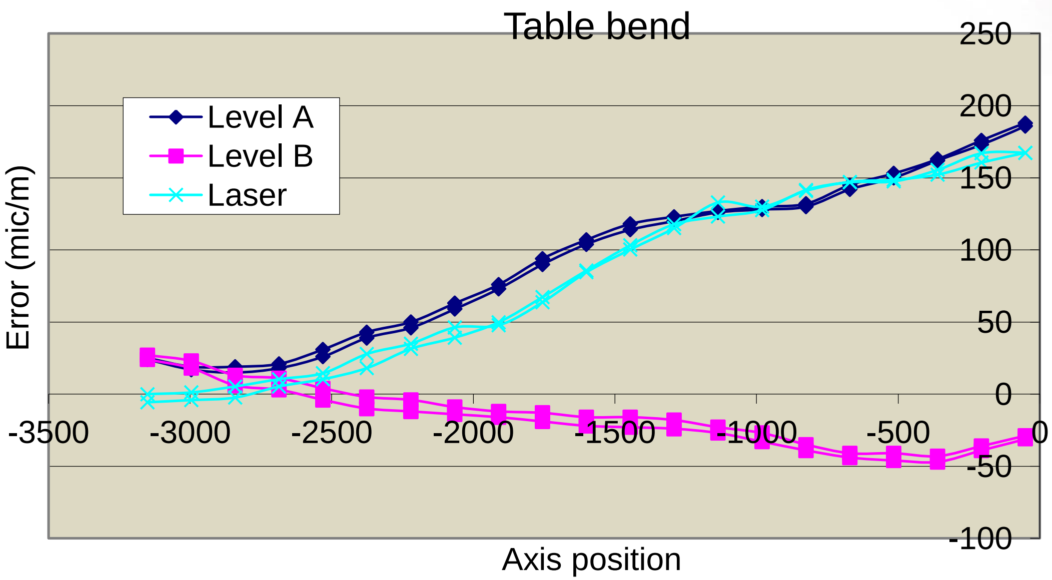


Finite stiffness

Uncertainty from finite stiffness

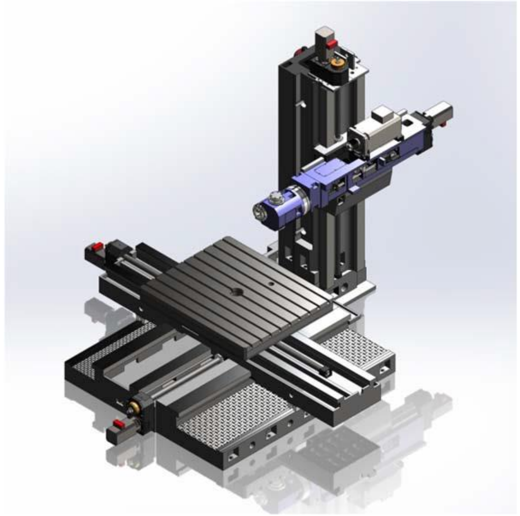
- Long machine table
- Significant bend 200µm/m
- Uncertainty in
  - reading from a laser interferometry
  - Squareness of C axis to X

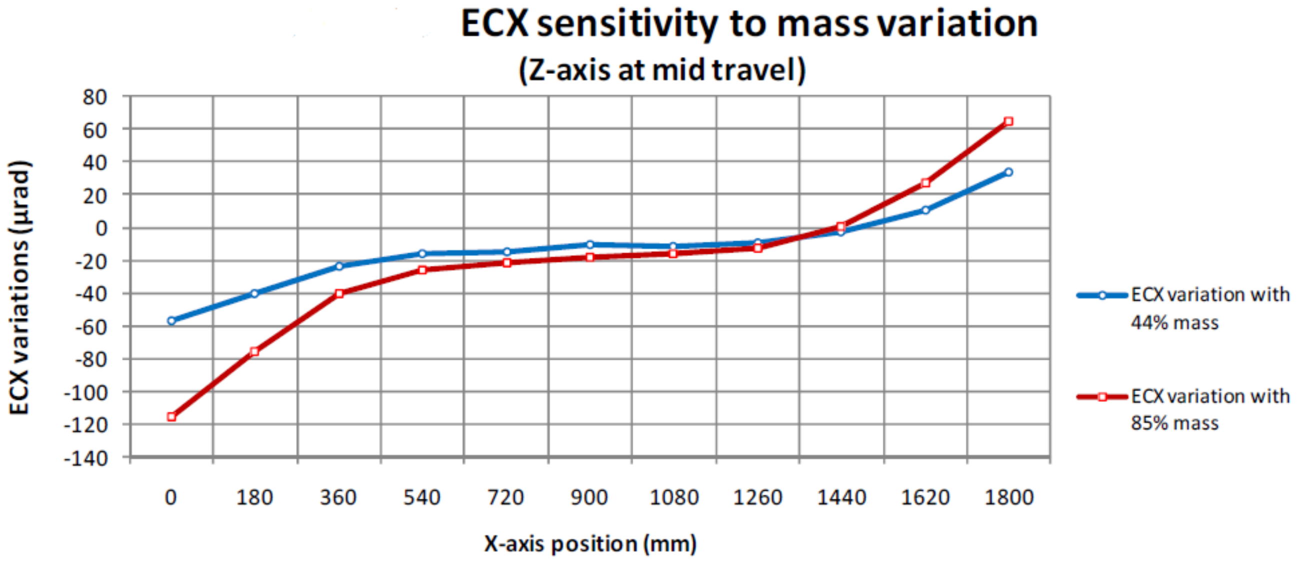




Variation in mass on table

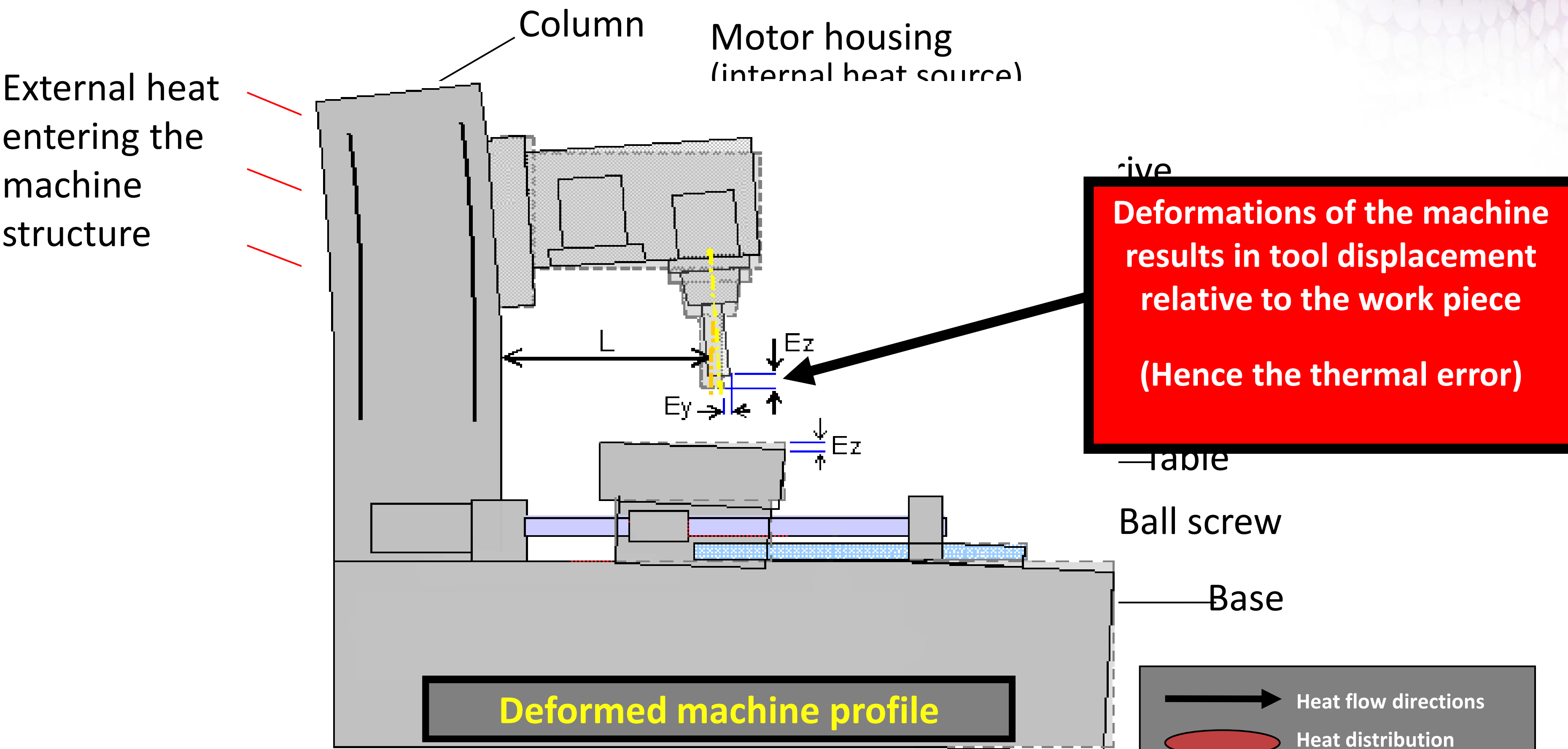
- The machine is often tested "unloaded"
  - Fixtures and the workpiece can have significant weight
- The distribution of the mass can cause distortion
  - Especially if table loads are mounted asymmetrically
- Own weight, fixture and workpiece mass variation affects geometry
  - Moving table example showed 90μrad increase in angular error with 1000Kg mass added.





Thermal deformation

Machine tool generic heat distributions

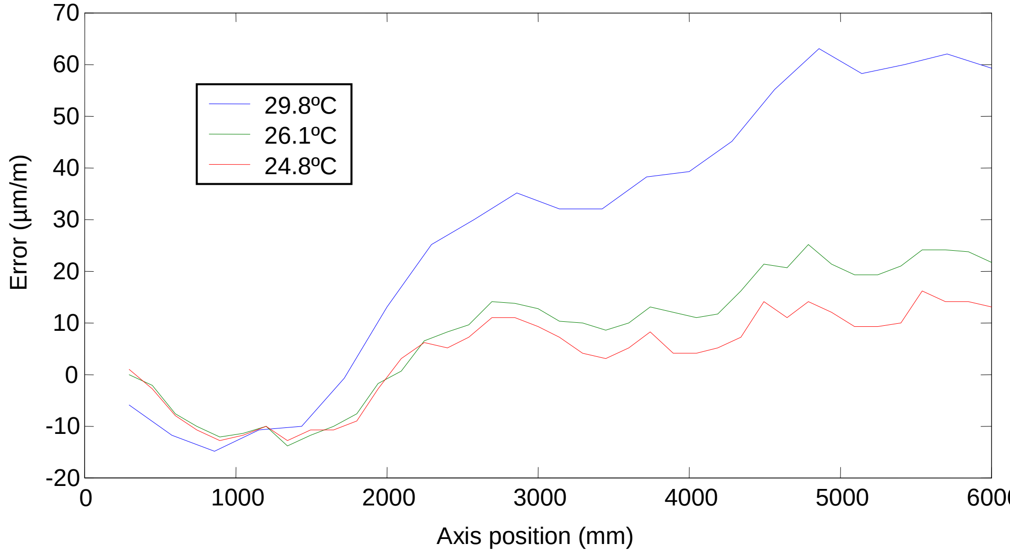


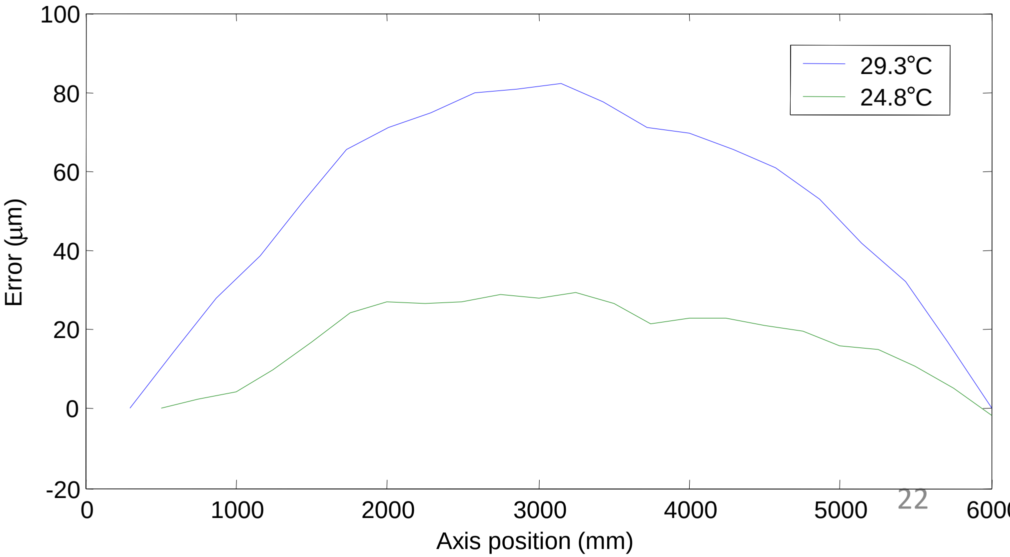
Environmental effect

- Traceability limited to conditions under which calibration made.
- Large 5-axis gantry in normal machine shop

(Late summer in northern Italy)

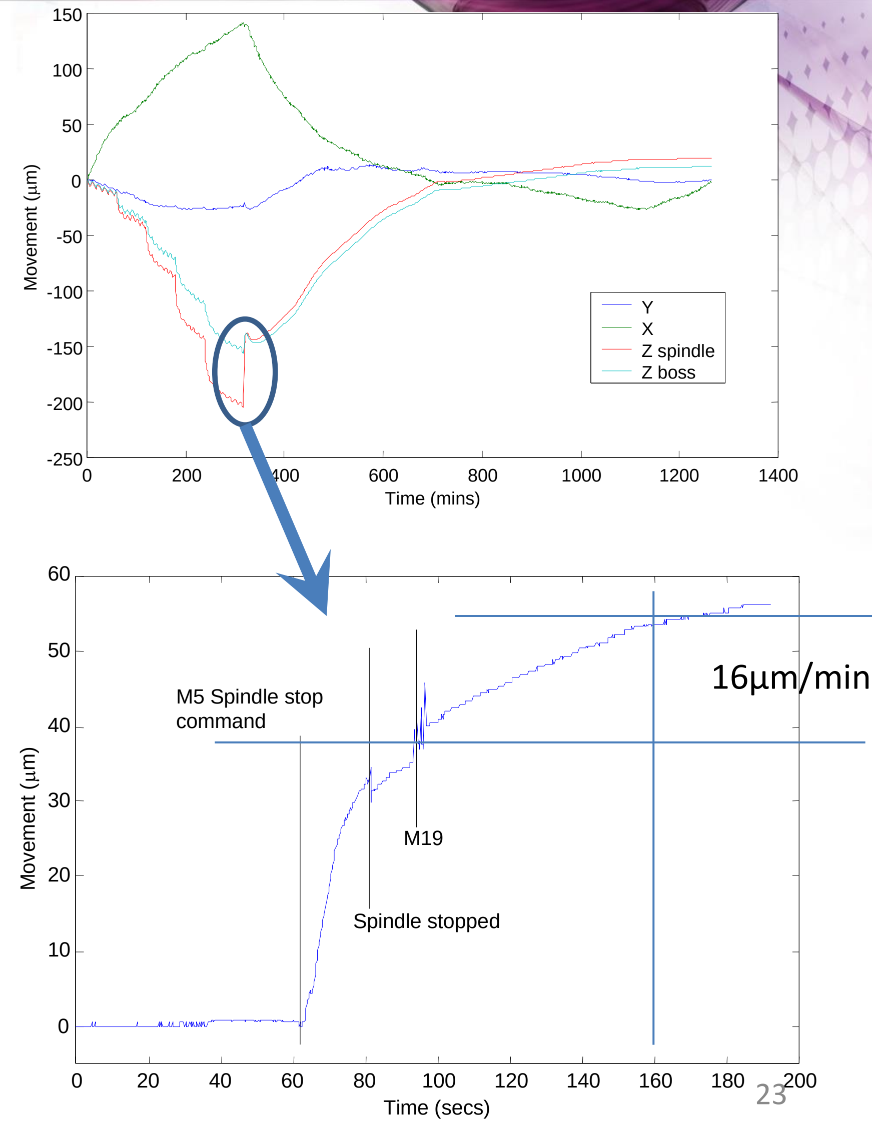
  - Angular change ≈10µrad/°C
  - Straightness ≈11µm/ °C





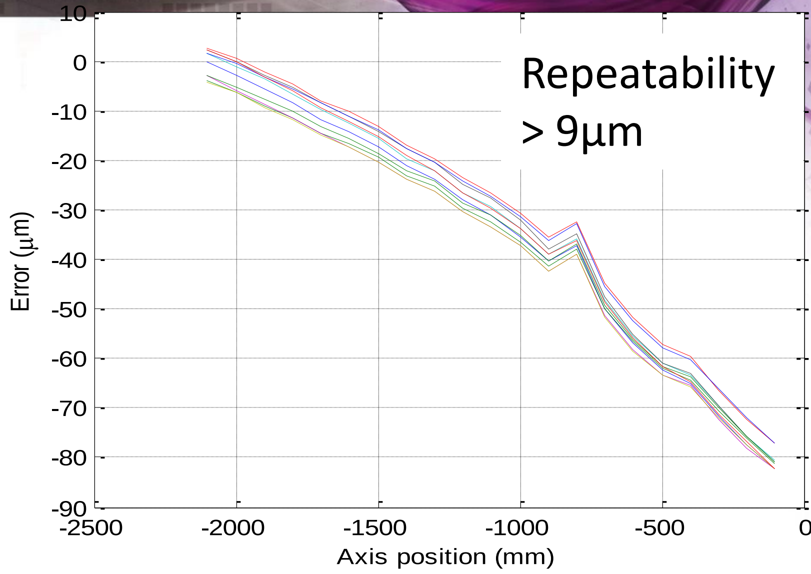
Rapid change in temperature

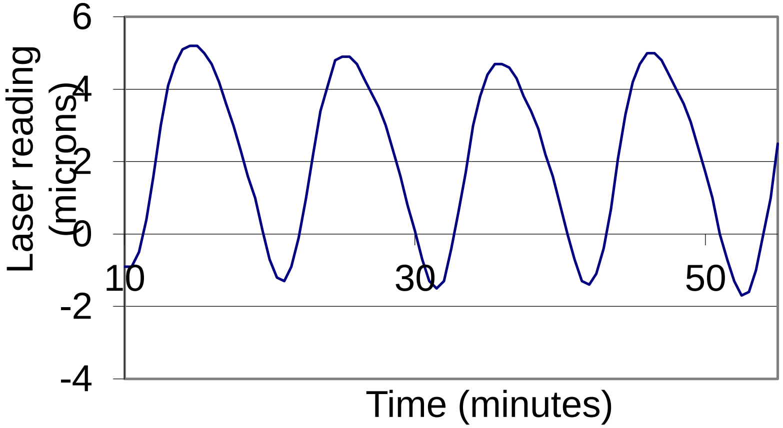
- Rapid heating when cutting
- Rapid cooling when not cutting
  - For example probing
- Geometric measurements usually taken under nominally stable conditions
- Rapid error in spindle axial direction from
  - spindle speed change or
  - spindle stop
- Mechanical and thermal effect
- Significant error between spindle stop command and probing cycle start



Unforseen thermal effect

- Standard axis positioning error measurement
  - Poor repeatability compared to expectation
- Position monitored (EVE)
  - Cyclic error of >5µm
  - Due to underdamped air chiller on the machine
  - Frequency dependent on the environmental temperature
- Time to complete measurement approximately 22 minutes
  - Included just over 1 cycle



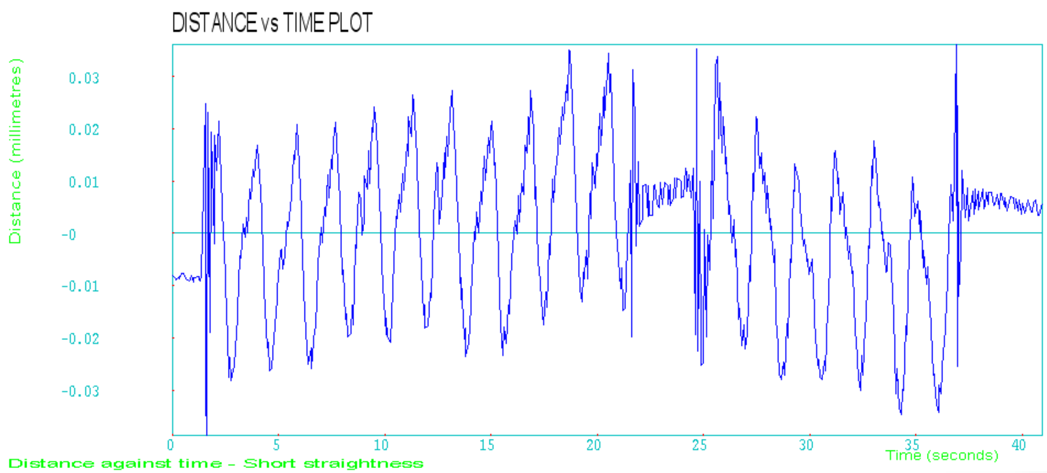


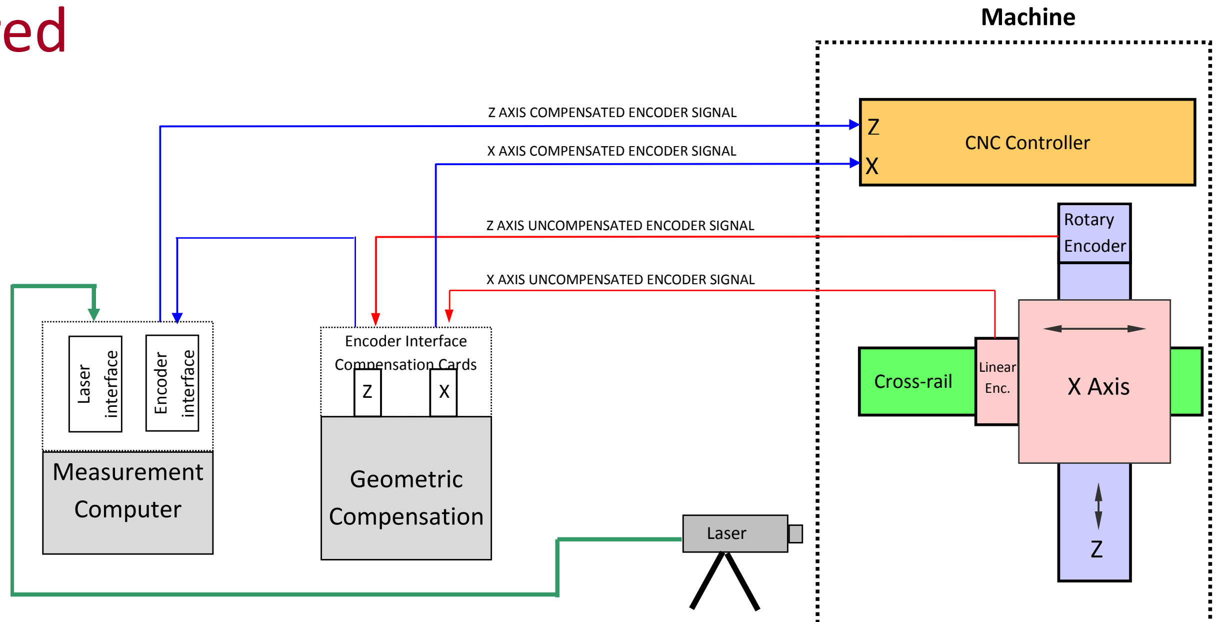
Errors due to motion

Dynamic versus quasi-static

Dynamic data capture

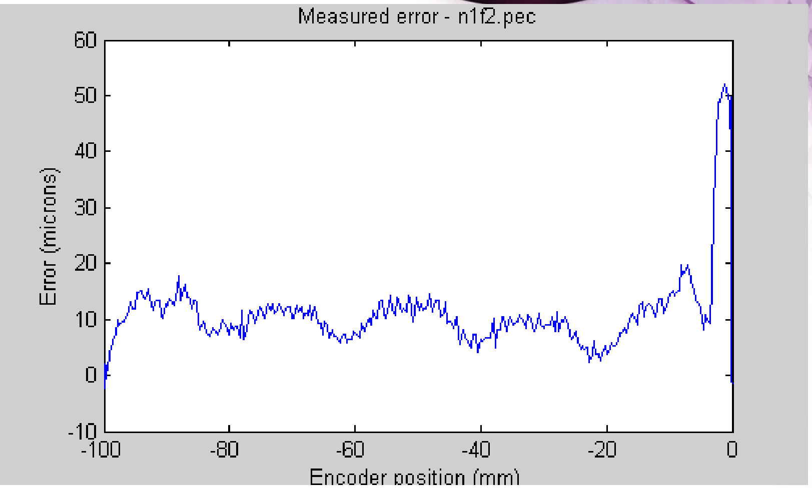
- Dynamic data capture
  - Not convenient, since actual and nominal positions must be synchronised.
  - Rarely performed
- Bespoke system required

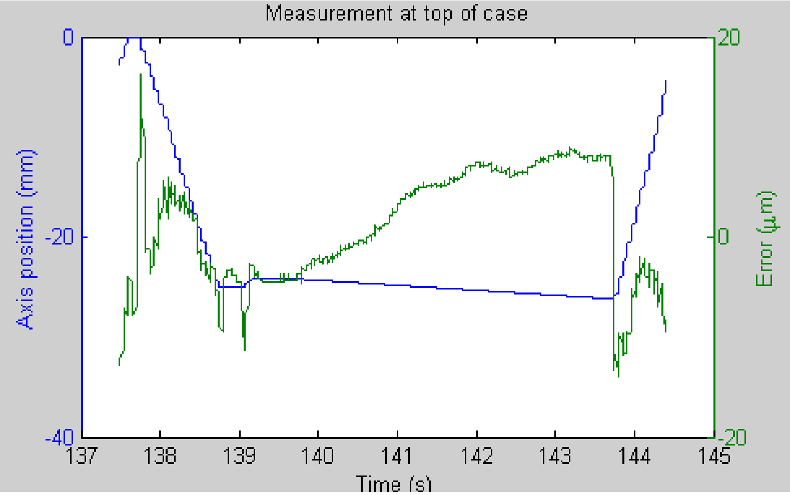


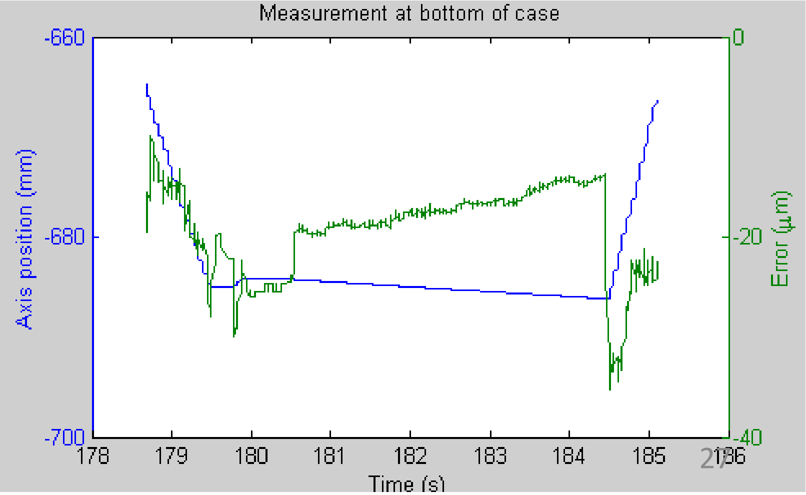


Dynamic errors - measurement

- Cyclic errors and acceleration effects can be detected
- Dynamic effects can be different with varying
  - location on an axis
  - speeds
  - size of motion
- Therefore difficult to quantify





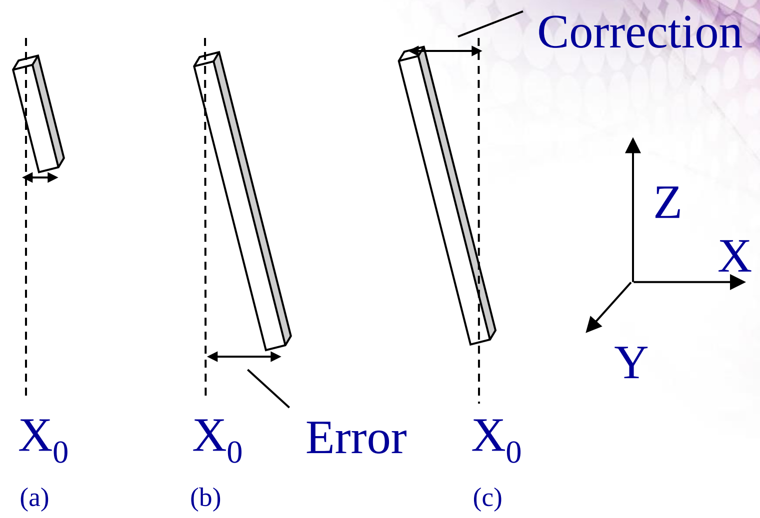


Numerical compensation

Numerical compensation

- Error compensation is the process of cancelling or correcting the effect of an error, usually by moving the axes of the machine.

- Can correct for errors that cannot easily be removed by error avoidance.



- Relatively inexpensive and easy to implement when compared to mechanical realignment.
- Flexible, since it can be updated to accommodate changes in error.
- Is not intended as a substitute for good mechanical design and build.

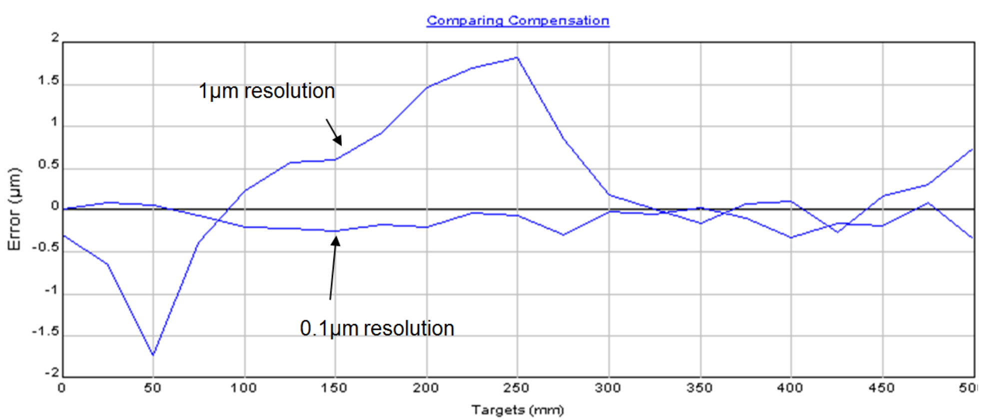
Numerical compensation methods

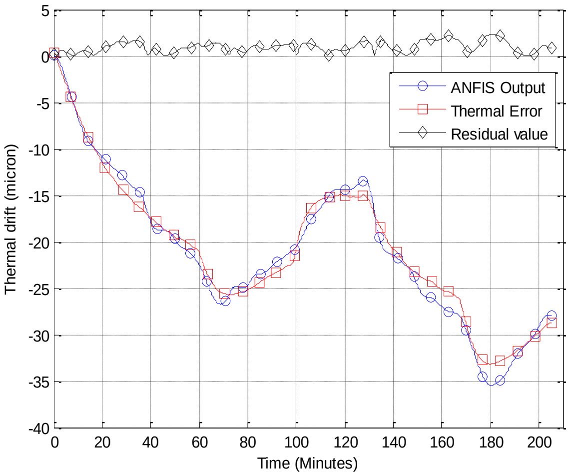
- Internal (Controller)
  - Part program modification
  - Programmable Logic Controller (PLC)
  - Inbuilt pitch and cross-axis
  - OEM application
- External
  - PLC
  - Feedback modification
    - PC based
    - Bespoke electronics

- Model types – commercially available
  - Error map
  - Simple linear expansion
  - Parametric equations
  - HTMs
- Model types – ongoing research
  - Black box
  - Artificial intelligence

Numerical compensation

- Electronic compensation is a powerful tool
  - Allows repeatable errors to be reduced without expensive mechanical action
- But it introduces uncertainty, which varies depending
  - upon the skill of the engineer performing the update
  - the quality of the data
  - The quality of the compensation system
  - (An ISO standard is in preparation to help address this issue).

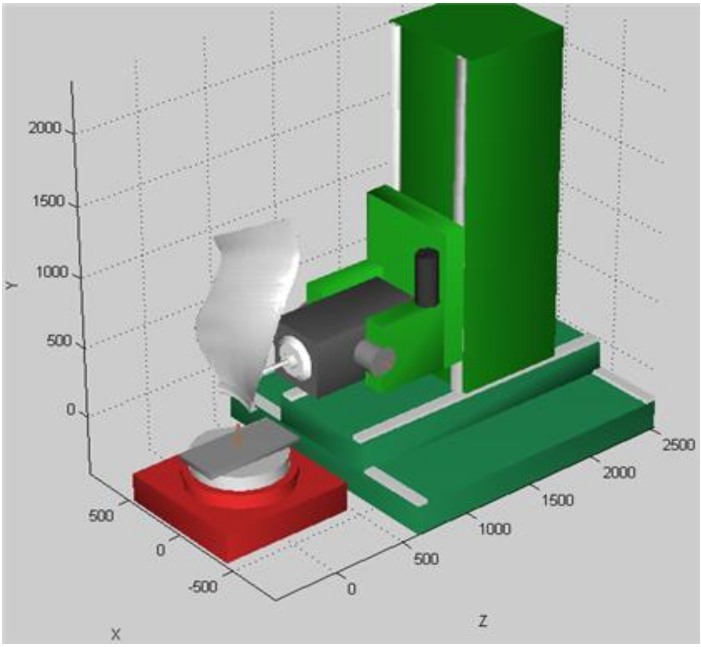


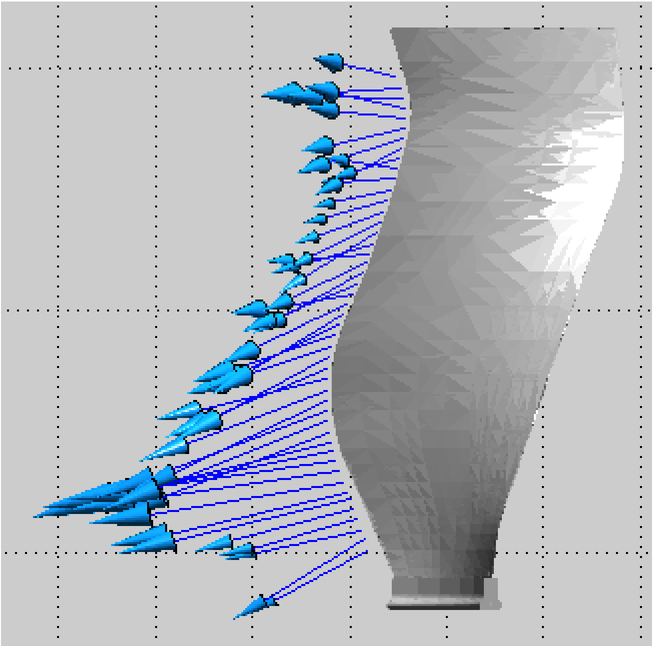


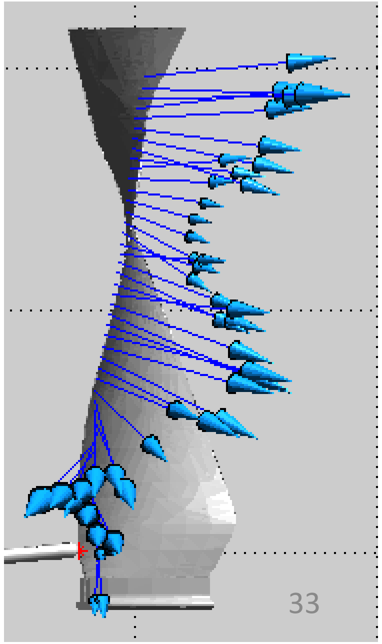
Simulation with measured data as a solution

Simulation of effects of errors

- Combining all machine error sources allows prediction of errors on probing (and machining) results
  - Magnitude and direction of errors represented by arrows.

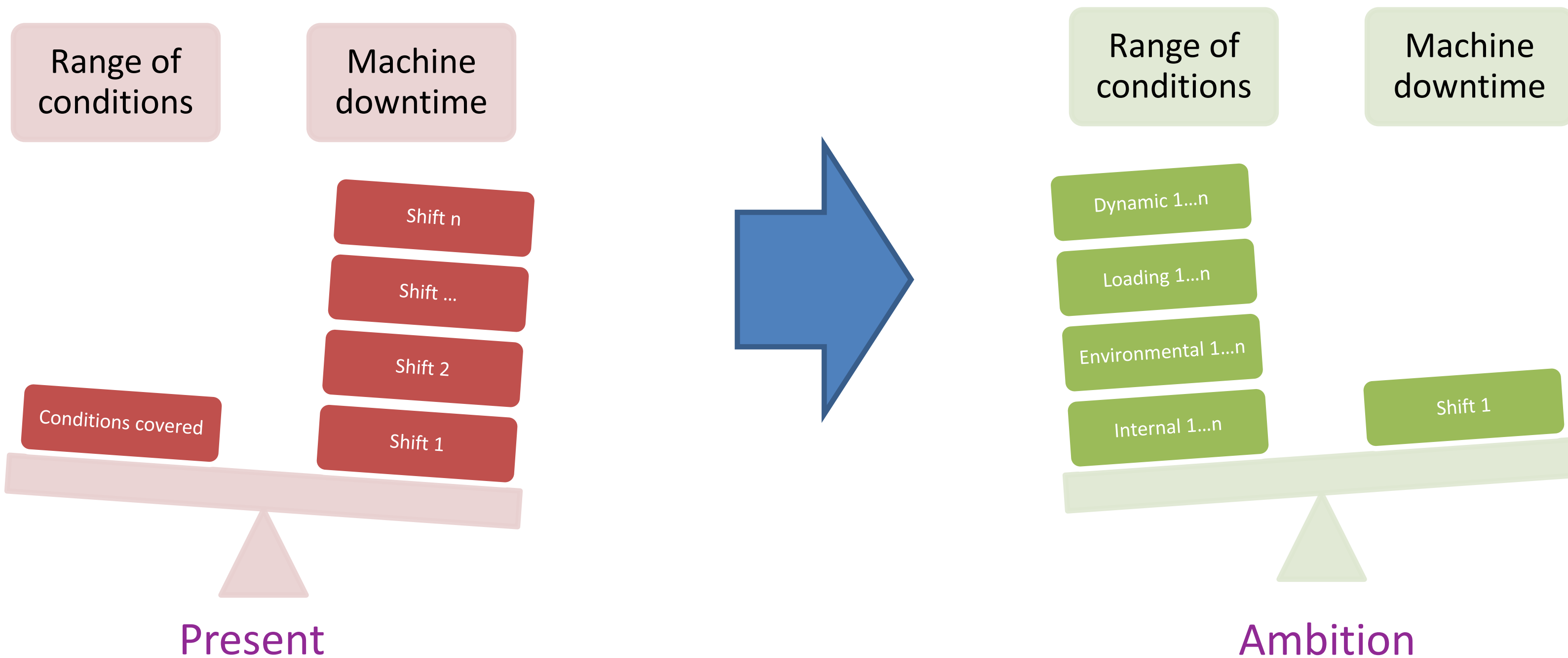






The future

- Measurement and simulation
  - dramatically reducing machine down-time for testing
  - simulate any conditions for more robust training
    - seasonal environmental variations,
    - new running conditions for new products,
    - agile manufacturing.



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