National Physical Laboratory

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Error sources in dimensional metrology

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Outline

- Dimensional metrology
- The Metrology Loop
- Error sources and mitigation

Dimensional Metrology

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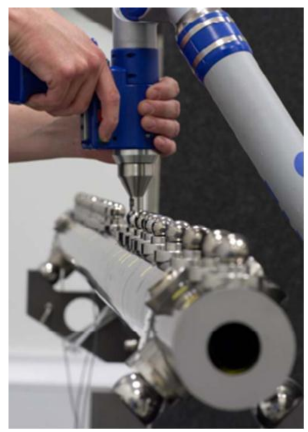
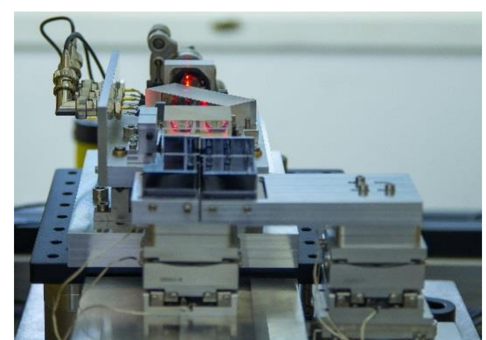
- 1D, 2D and 3D
- Contact or Non-contact
- Range based, angle based or a combination of both
- Scales from pm to …

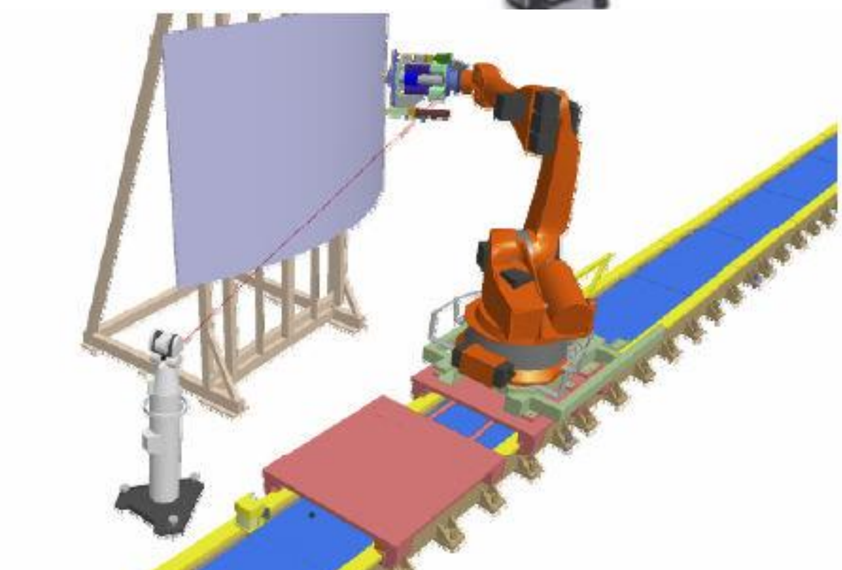




The Metrology Loop

- A metrology loop is the closed path containing all elements between the sensor and the part that affect the measurement.
- Often the metrology loop has elements in common with the structural or force loop.
- **Changes in the metrology loop** due to, for example, temperature change, vibration or structural forces, **are indistinguishable from changes in the dimension being measured**.

The Metrology Loop



Error Sources and Mitigation

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- Thermal
- Refraction & Refractive index gradient
- Mechanical errors
- Geometric errors

Error Sources and Mitigation

- Thermal effects
  - One of the biggest potential sources of error in dimensional metrology!
  - ISO 1: "*The standard reference temperature for geometrical product specification is fixed at 20 °C*"
  - Dimensions measured at T ≠ 20 °C must be corrected

$$L_{20} = L_T[1 - \alpha(T-20)]$$

α is coefficient of thermal expansion

e.g. $\alpha_{steel} = 12\times10^{-6}\ \mathrm{K}^{-1}$, $\alpha_{aluminium} = 23\times10^{-6}\ \mathrm{K}^{-1}$

  - Thermal expansion affects the instrument too
    - Distorts the metrology loop

Error Sources and Mitigation

- Thermal effects *continued*
  - Mitigation
    - Use low CTE materials for critical parts of the metrology loop *e.g*. *Invar* or *Zerodur*
    - Minimise uncertainty in thermal expansion correction by controlling temperature close to 20 °C
      - Active environmental control
      - Local insulation
      - Avoid handling parts
      - Allow time for thermal stabilisation

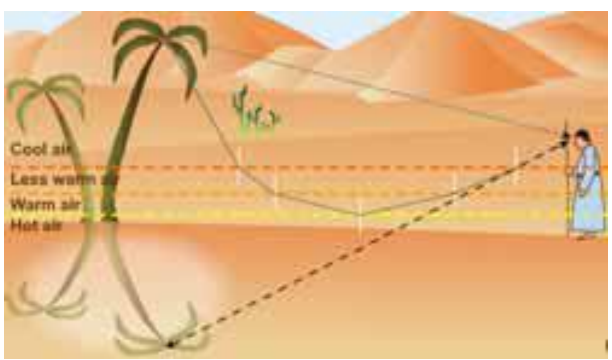
Error Sources and Mitigation

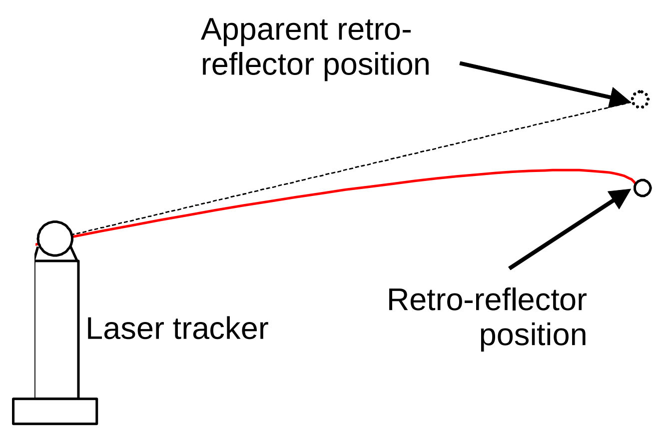
- Refractive index
  - Affects *optical length* measurements *e.g*. interferometers
  - Refractive index, n, determines speed of light in a medium, c'. So distances measured in terms of the speed of light must be corrected.

    $c' = c_0/n$ c_0 = speed of light in vacuum
  - n at standard temperature and pressure ~ 1.00027
  - $dn/dT \sim -1\times10^{-6}\ \mathrm{K}^{-1}$
  - $dn/dP \sim 2.7\times10^{-7}\ \mathrm{hPa}^{-1}$
  - Can calculate n from air temperature and pressure readings using *e.g.* Edlen's formula

Error Sources and Mitigation

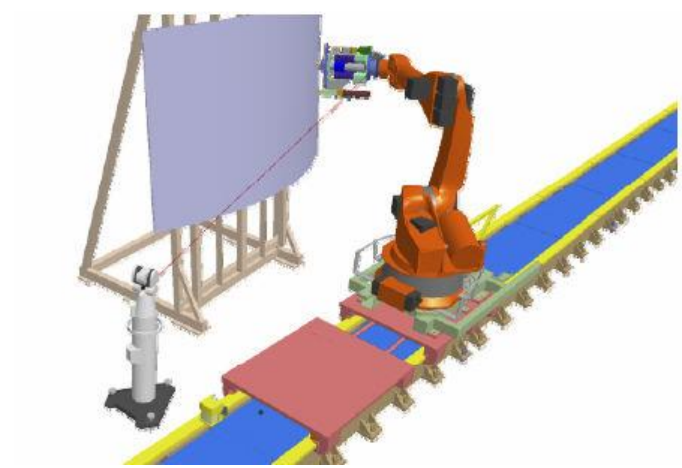
- Refractive index gradient
  - Gradient normal to direction of propagation of a beam bends the beam
  - This is how a mirage is formed!
  - Affects optical *angle* measurements *e.g*. laser tracker





Error Sources and Mitigation

- Mechanical - Stiffness of metrology loop
  - Instrument *e.g*. CMM structure
  - Instrument support *e.g*. laser tracker tripod
  - Part support/clamping
  - Isolate force loop from metrology loop

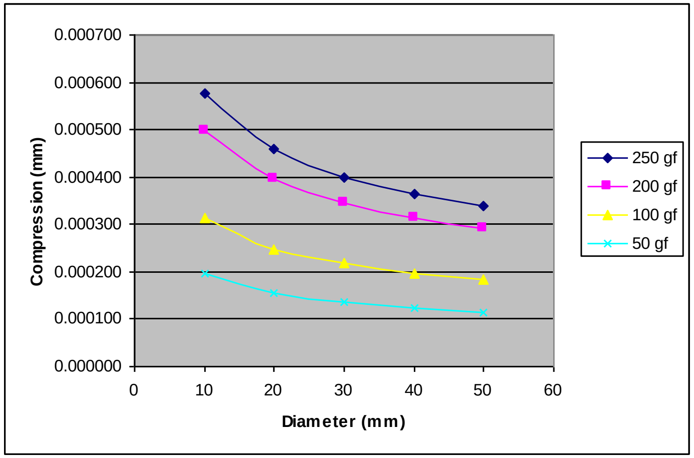


Error Sources and Mitigation

- Mechanical - Vibration induced the metrology loop
  - Eliminate/isolate source
  - Isolate metrology loop
  - Stiffen structure – high resonant frequency
  - Also air movement in optical metrology systems

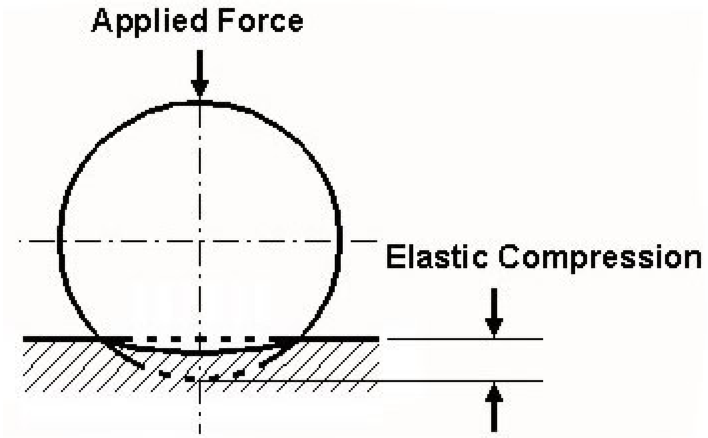
Error Sources and Mitigation

- Mechanical – elastic compression
  - Occurs whenever mechanical probing takes place
  - Depends on contact force
  - Geometry of component (*e.g*. flat, sphere, cylinder)
  - Component and probe materials
  - Type of contact (*e.g*. point, line)



Compression corrections for tungsten carbide spheres between flat steel anvils for various forces

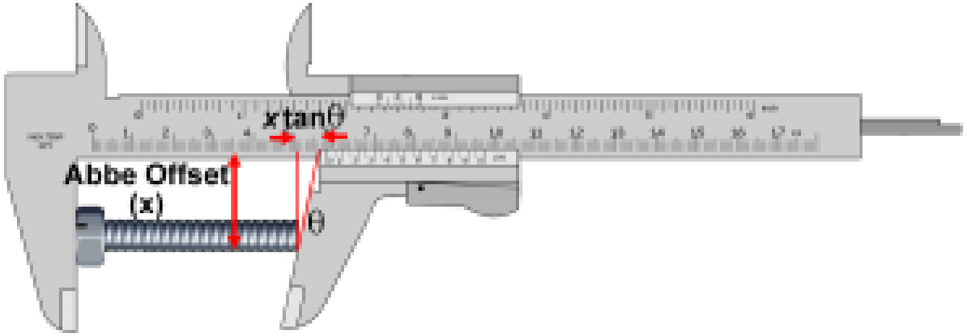
NPL GPG 80



http://emtoolbox.nist.gov/Main/Main.asp

Error Sources and Mitigation

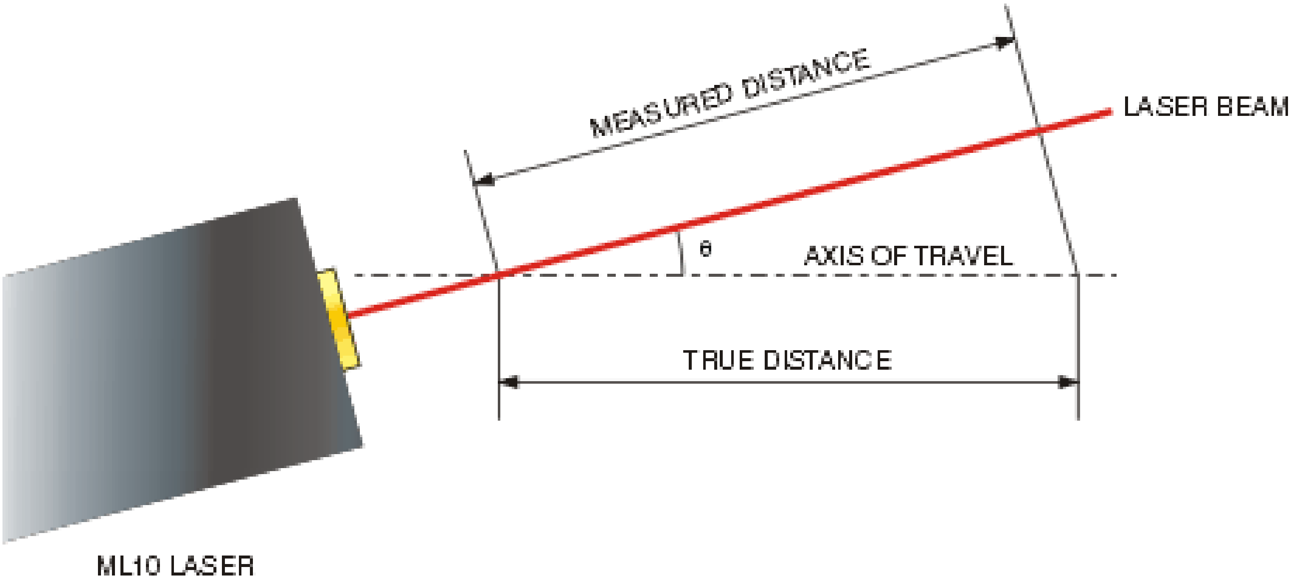
- Alignment - Abbe error
  - Measurement scale is not in line with the object being measured – Abbe offset, x.
  - Straightness of axis or sloppy fit of calliper causes angle between jaws, θ.
  - Eliminate by aligning scale coaxially with part, or compensate my measuring x and θ.



Images from www.muelaner.com

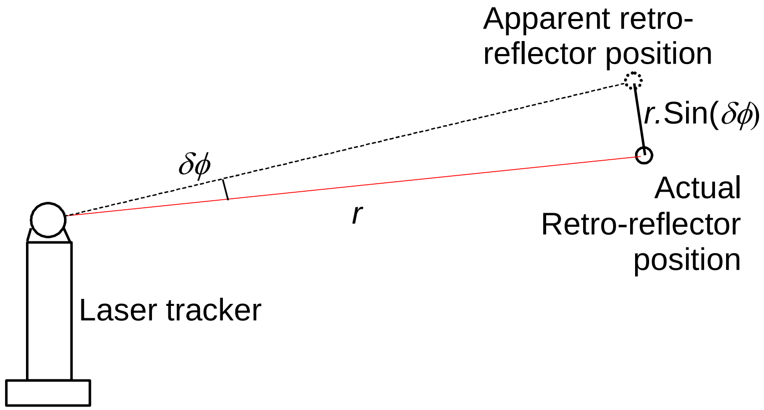
Error Sources and Mitigation

- Alignment - Cosine error
  - Angular misalignment, θ, between scale, or axis, and part.
  - Length error, $\Delta L = L(1 - \cos\theta)$.
  - Minimise by minimising θ.



Error Sources and Mitigation

- Alignment – Sine error
  - Occurs in angle-based coordinate metrology due to angle measurement error, $\delta\phi$.
  - Error proportional to range, *r*.
  - Reduce coordinate error by reducing $\delta\phi$ and/or *r*.
  - Eliminate by measuring coordinates in terms of range only.



Conclusion

- There are many sources of error in dimensional metrology
- Careful control of the metrology loop can help minimise or eliminate many sources of error

THANK YOU

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