Sensor development – State-of-the-art review

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MetMap 22 - 23 January 2019
AMRC Sheffield, UK

www.cranfield.ac.uk

Overview

- Introduction
- Dimensional metrology tools
- Non-dimensional sensing
- Future requirements

Surface Engineering and Precision Institute

We envision a UK manufacturing sector with world abundant *Engineering for life* products for extreme service.

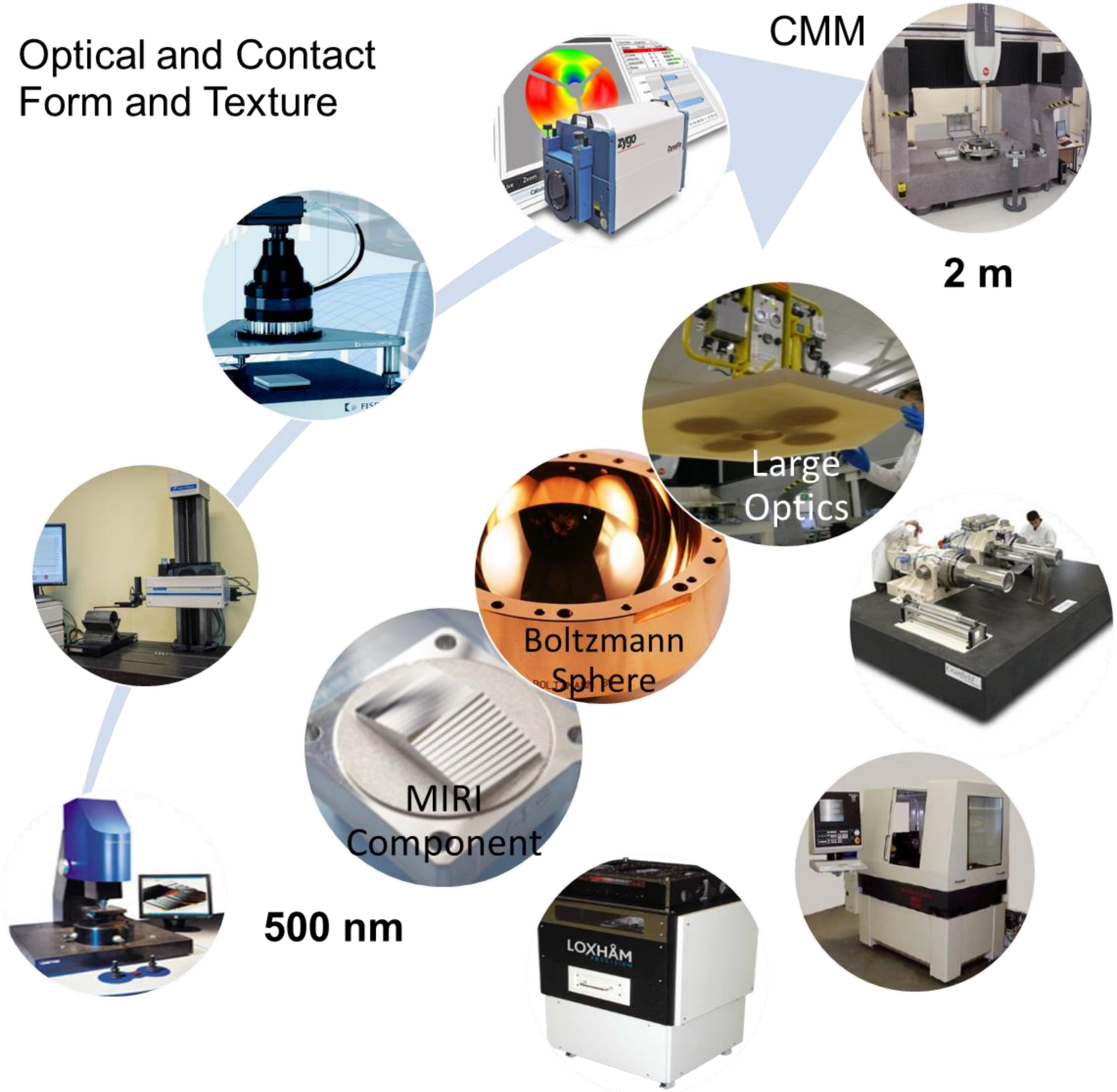
Advanced Functional Coatings supported by the National High Temperature Surface Engineering Centre, Sol-Gel Centre and Nanotechnology Labs.

Precision Device Manufacturing: Cranfield Nano, specialising in creating new forms of materials for detectors, sensors, biosensors, and actuators,

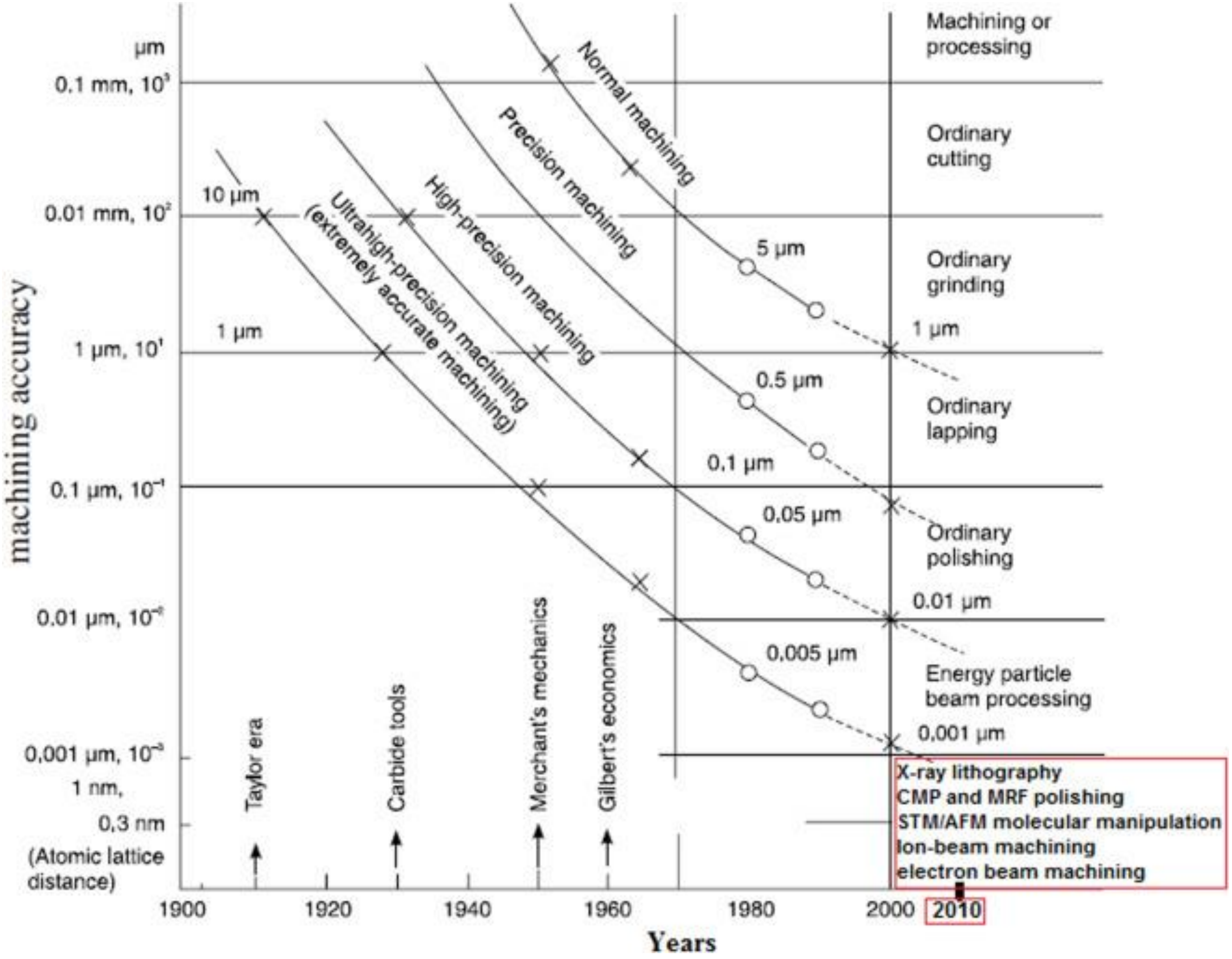
In-Process Metrology: metrology applied as closely as possible to the point of manufacture supported by world-class Precision and ultra precision engineering laboratories

QA/QC

Optical and Contact
Form and Texture

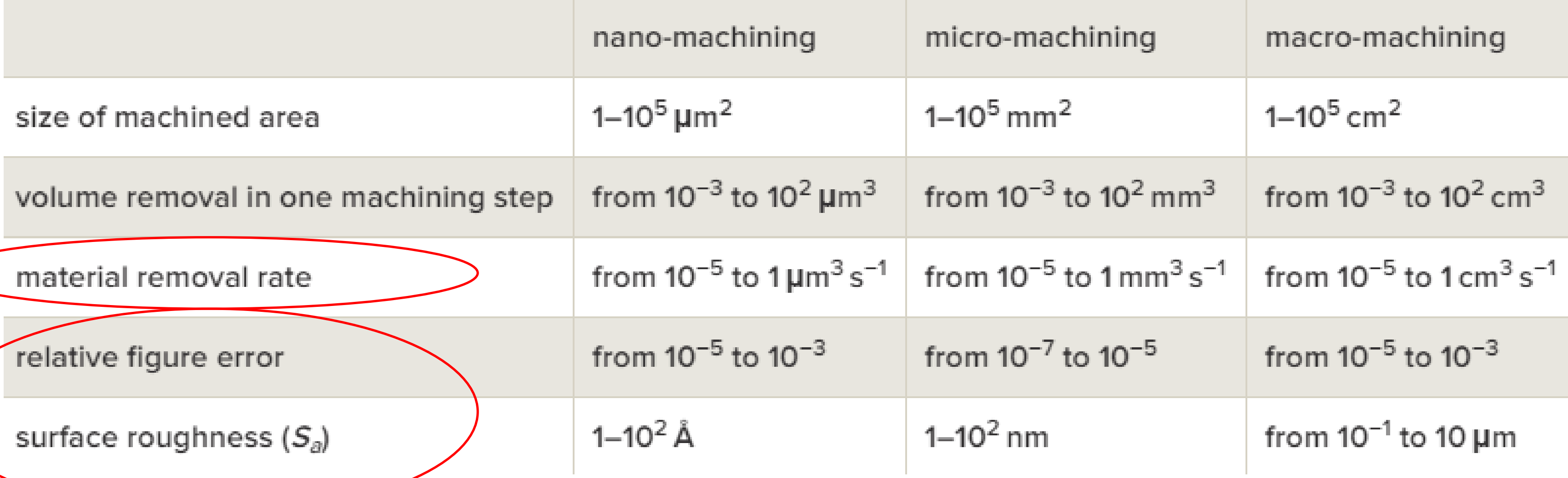


A bit of context – Taniguchi's chart



Goel S *et al* (2015) *Int. J. Mach. Tools Manuf.* **88** 131-164

Achievable surface quality

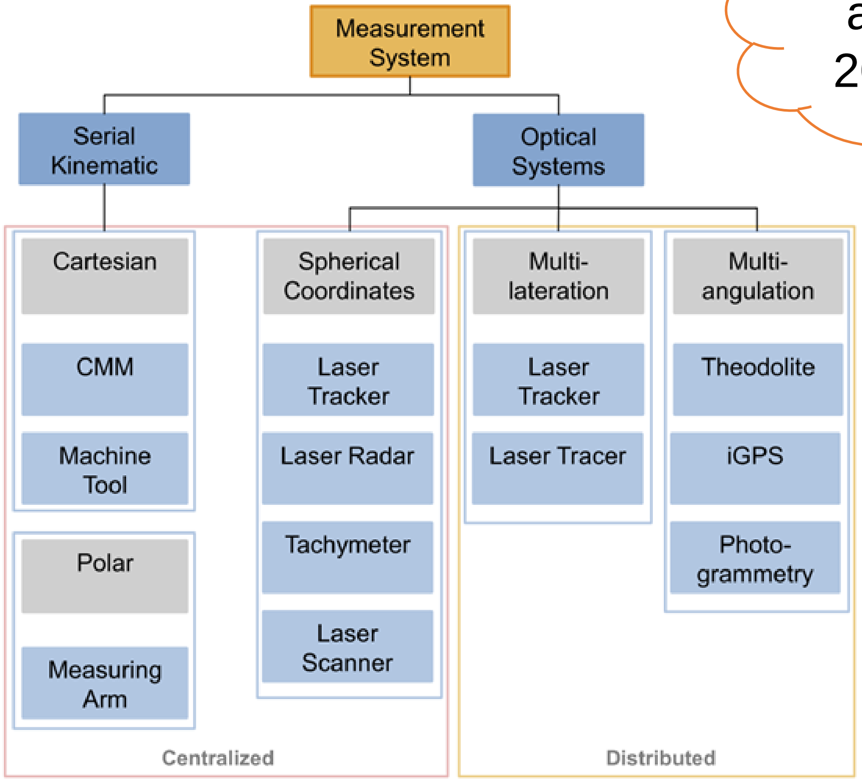


	nano-machining	micro-machining	macro-machining
size of machined area	1–10^5 μm^2	1–10^5 mm^2	1–10^5 cm^2
volume removal in one machining step	from 10^{-3} to 10^2 μm^3	from 10^{-3} to 10^2 mm^3	from 10^{-3} to 10^2 cm^3
material removal rate	from 10^{-5} to 1 μm^3 s^{-1}	from 10^{-5} to 1 mm^3 s^{-1}	from 10^{-5} to 1 cm^3 s^{-1}
relative figure error	from 10^{-5} to 10^{-3}	from 10^{-7} to 10^{-5}	from 10^{-5} to 10^{-3}
surface roughness (S_a)	1–10^2 Å	1–10^2 nm	from 10^{-1} to 10 μm

Brinksmeier E and Preuss W (2012) *Philos. Trans. R. Soc. A: Math. Phys. Eng. Sci.* **370** 3973-3992.

Large-Scale Metrology (LSM)

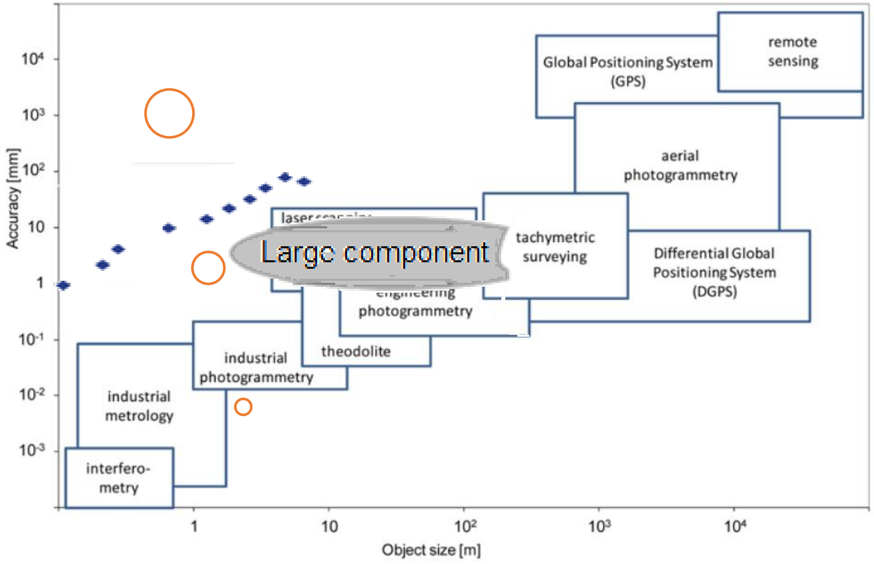
Challenging applications
20 µm in 4 m



- Measurement System
  - Serial Kinematic
    - Cartesian
      - CMM
      - Machine Tool
    - Polar
      - Measuring Arm
  - Optical Systems
    - Spherical Coordinates
      - Laser Tracker
      - Laser Radar
      - Tachymeter
      - Laser Scanner
    - Multi-lateration
      - Laser Tracker
      - Laser Tracer
    - Multi-angulation
      - Theodolite
      - iGPS
      - Photo-grammetry

Centralized

Distributed



Schmitt RH *et al.* (2016) CIRP Annals **65** 643-665

Franceschini F *et al.* in *Distributed Large-Scale Dimensional Metrology* Springer (2011)

Tactile

Available with contact and non-contact probes

Weckenmann A et al.(2004) *CIRP Annals* **53** 657–684

Weckenmann A et al. (2006) Meas Sci Technol **17** 504-509

Large CMM-s (5 m)

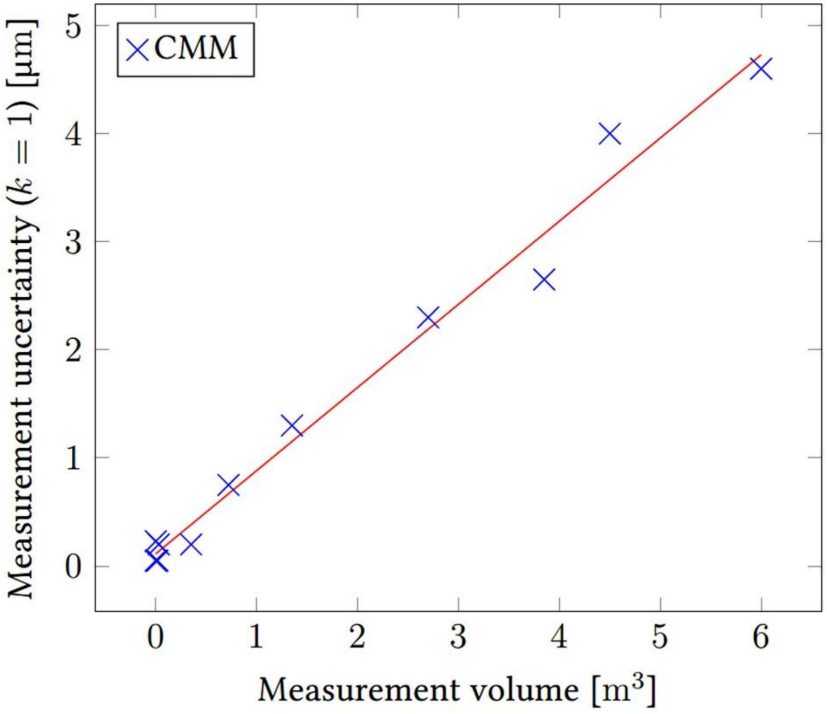
7 µm + L/250 µm

Schmitt RH *et al.* (2016) CIRP Annals **65** 643-665

Micro CMM-s

probe errors in excess of 50 nm

Thalmann R *et al. (2016) Appl. Sci.* ***6*** 150



Norman J (2019) PhD Thesis

Optical

Laser Tracker

Lau K *et al.* (1986) *Prec. Eng.* **8** 3-8

Muralikrishnan B (2016) *Prec. Eng.* **44** 13-28

$$[0.3^2 + (0.4 \times 10^{-3} L)^2]^{1/2}\ \mu\text{m}$$

Umetsu K (2005) *Meas. Sci. Technol.* **16** 2466-2472

Laser Tracers

0.2 µm + 0.3 µm/m (k=2)

Hughes EB *et al.* (2000) CIRP Annals **41** 391-394

FSI (Frequency Scanning Interferometry)

40 µm in 10 m × 5 m × 2.5 m

Dale J *et al.* (2014) *Opt. Exp.* ***22*** 24869-24893

Other techniques are less accurate:

Coherent laser radars

Laser line scanners

Photogrammetry

Schmitt RH *et al.* (2016) CIRP Annals **65** 643-665

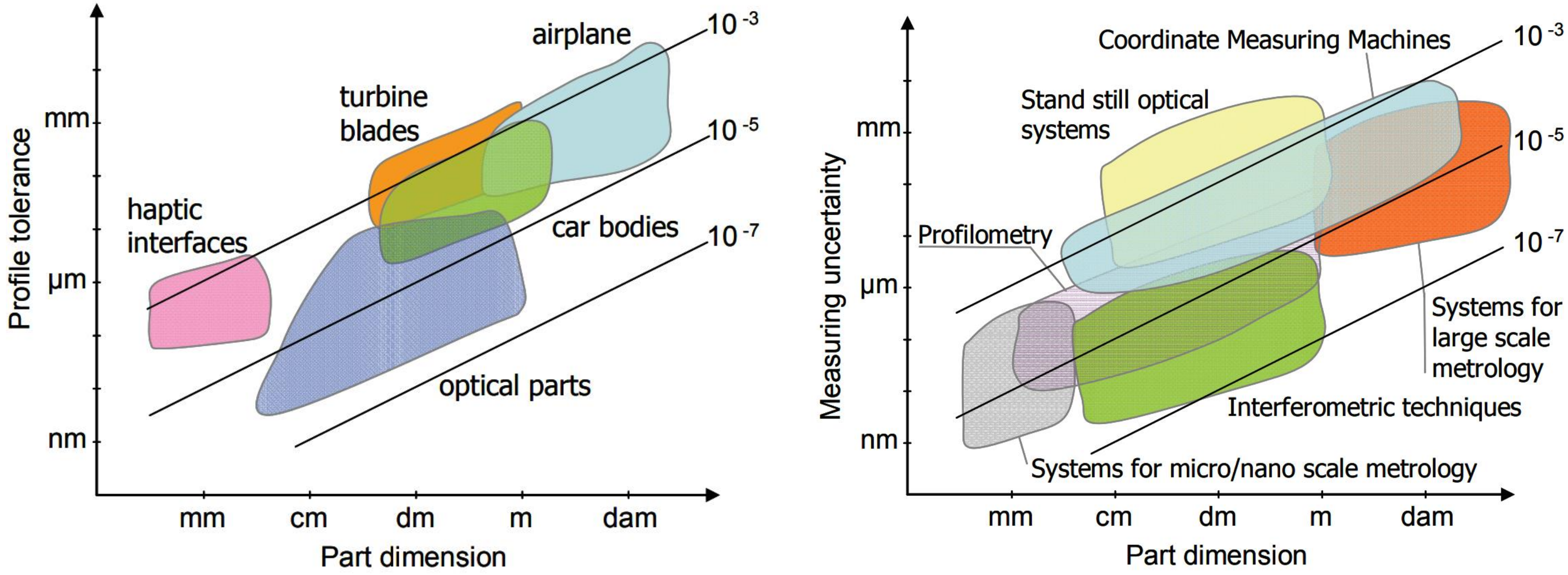
Various form measurement interferometric configurations are able to achieve sub-nanometre measurement repeatability.

Wyant JC (2018) Proc. SPIE **10749** 107490P

Issues with Lateral Dynamic Range v measurable slope (Loughborough talk)

Medium to small scale

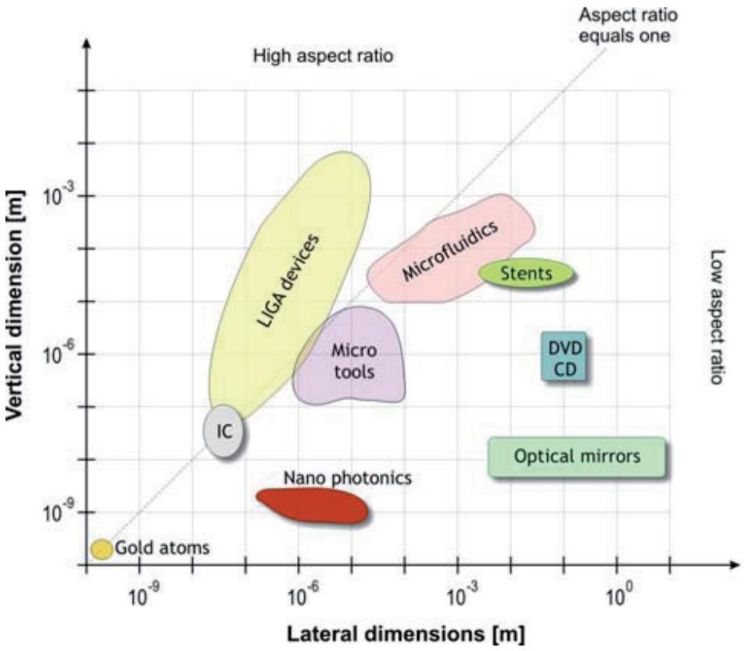
1:5 ratio uncertainty tolerance difficult to achieve

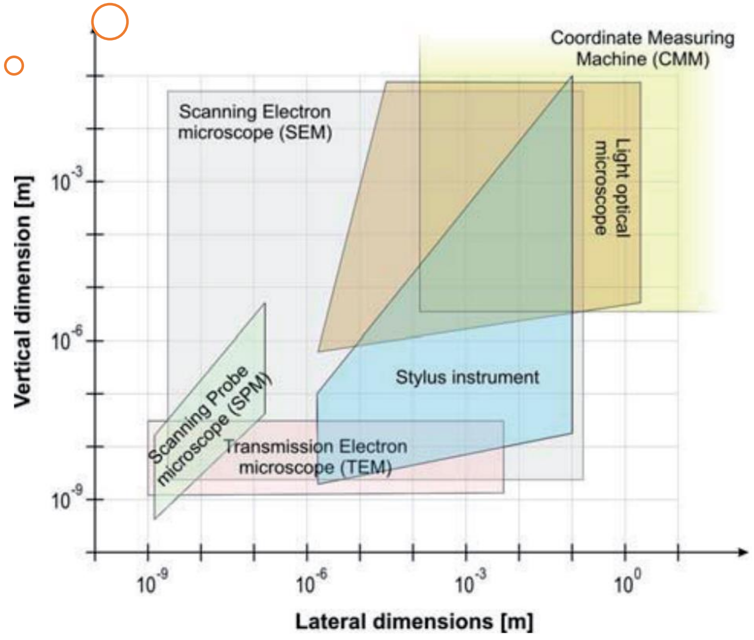


Savio E *et al.* (2007) CIRP Annals **56** 643-665

Micro and below …

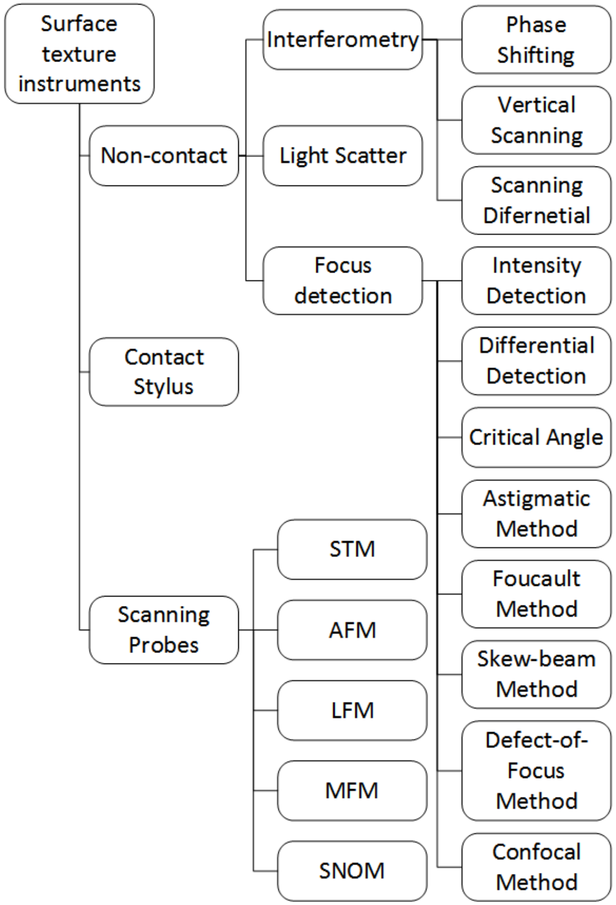
Aspect ratio!



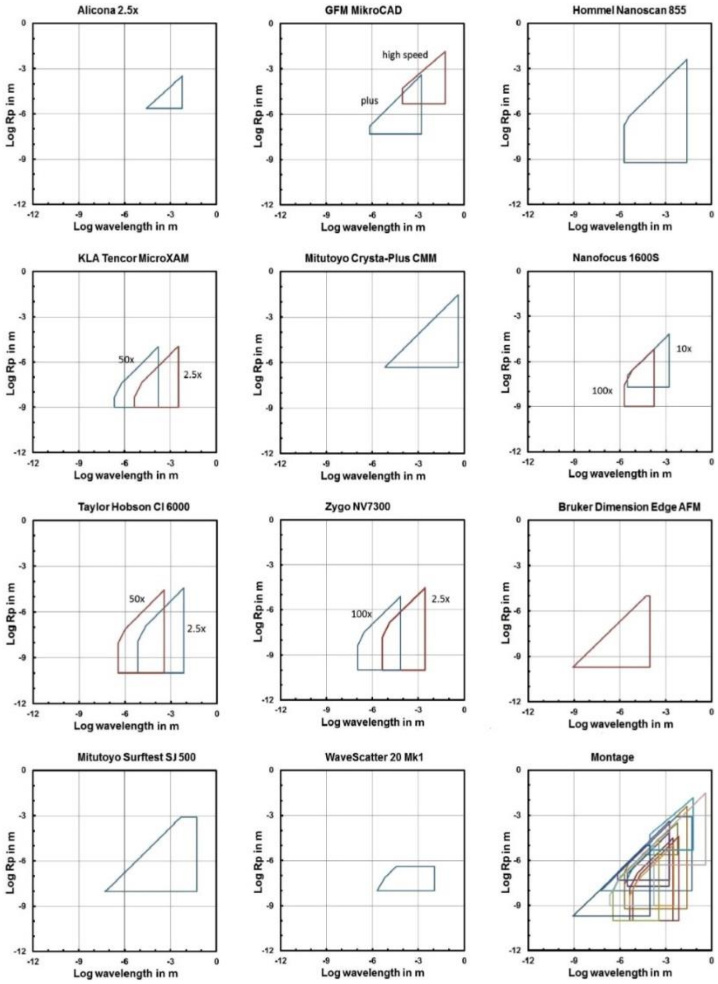


Hansen HN *et al.* (2006) CIRP Annals **55** 721-743

Surface texture (ISO25178 standards)



- Surface texture instruments
  - Non-contact
    - Interferometry
      - Phase Shifting
      - Vertical Scanning
      - Scanning Difernetial
    - Light Scatter
    - Focus detection
      - Intensity Detection
      - Differential Detection
      - Critical Angle
      - Astigmatic Method
      - Foucault Method
      - Skew-beam Method
      - Defect-of-Focus Method
      - Confocal Method
  - Contact Stylus
  - Scanning Probes
    - STM
    - AFM
    - LFM
    - MFM
    - SNOM



Rosen S *et al.* (2011) *Surf. Topogr.: Metrol. Prop*. **2** 014005

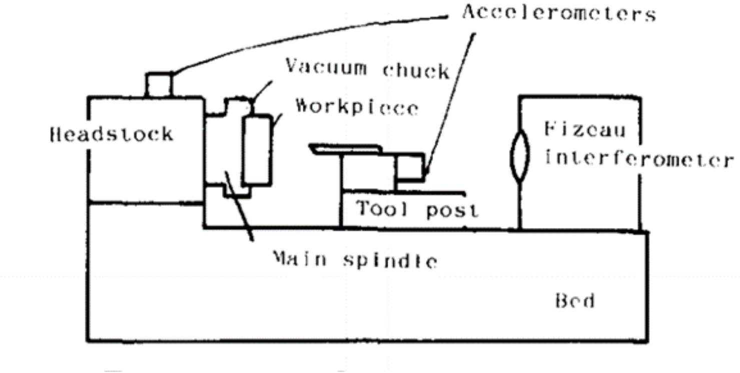
On-machine sensors

Mostly developed for two reasons:

- **Tool positioning and alignment**
- **Error compensation**

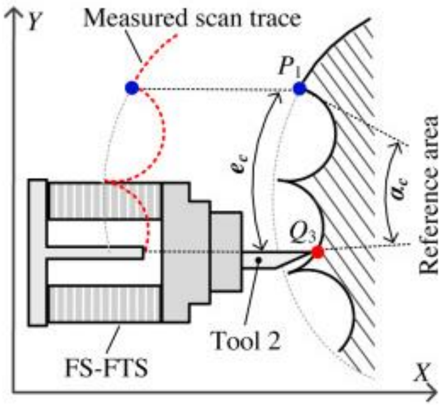
Added benefits:

- **QA/QC**
- **Process monitoring**



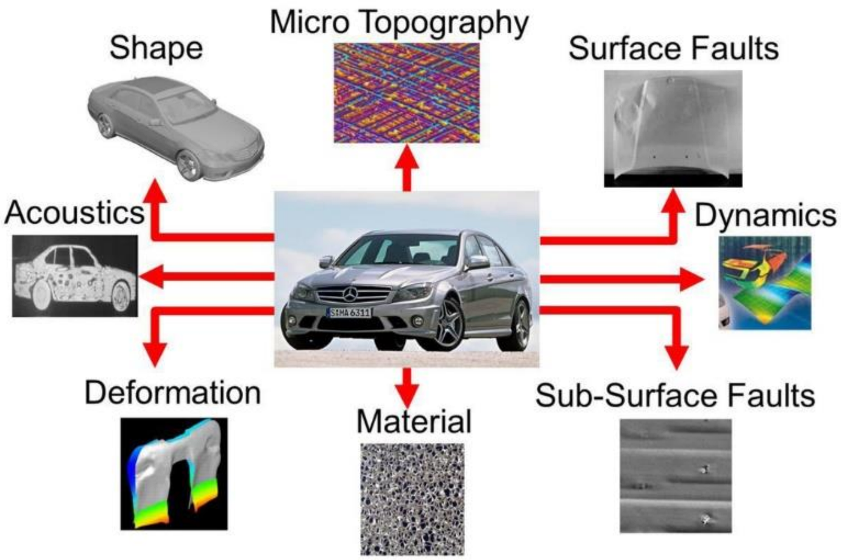
Nomura T *et al.* (1992) *Prec Eng* **14** 155-159

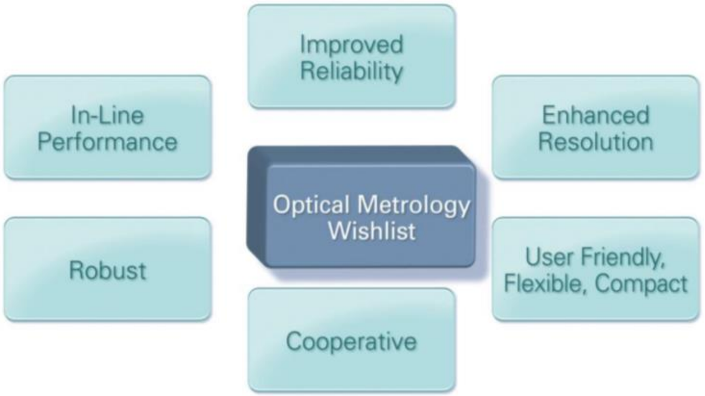
- Various interferometric techniques
- Photogrammetry
- Fringe projection
- 3D microscopes (ST)
- Optical and contact probes
- Laser trackers
- AFMs



Gao W *et al.* (2013) *CIRP Annals* **62** 523-526

Sensors requirements

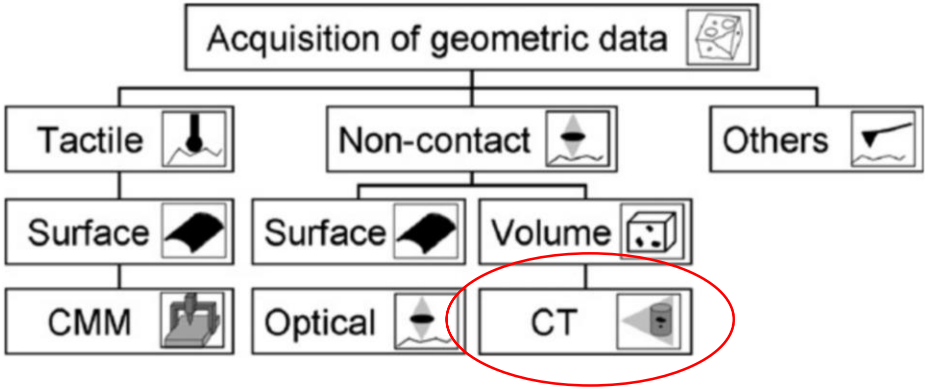




Osten W (2016) *Proc. SPIE* **9960** 99600P

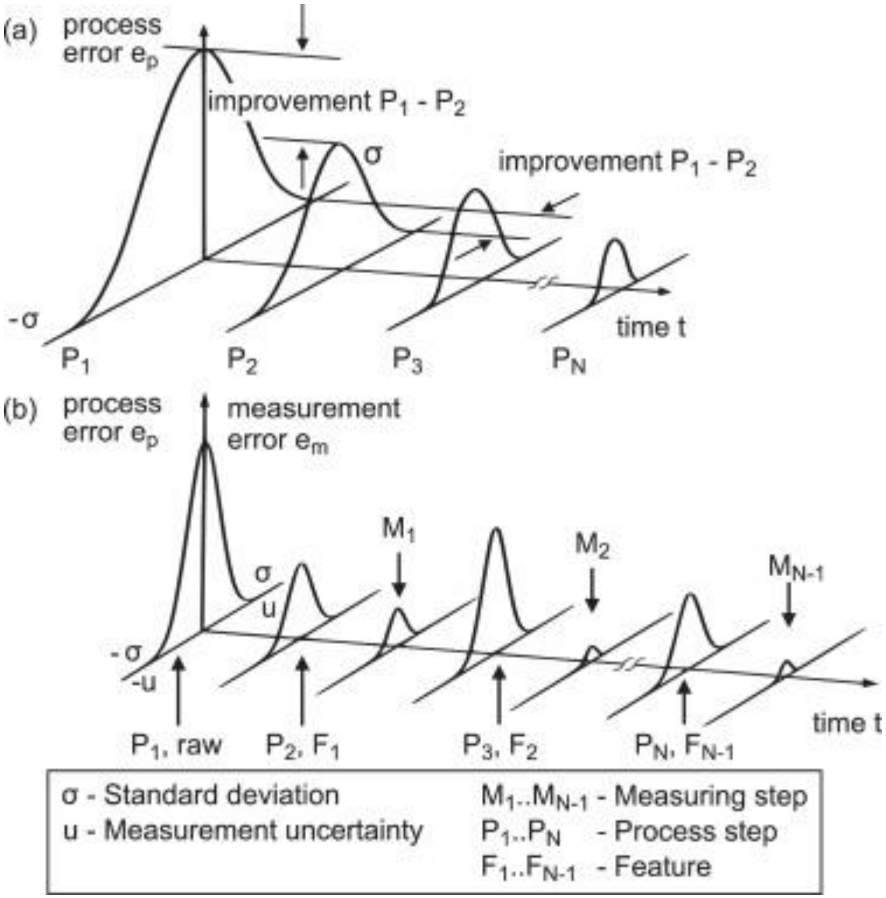
Multi-Sensor Data Fusion

Geometrical



Weckenmann A *et al.* (2009) *CIRP Ann.* **58** 701-721

What do we try to achieve and in which context?

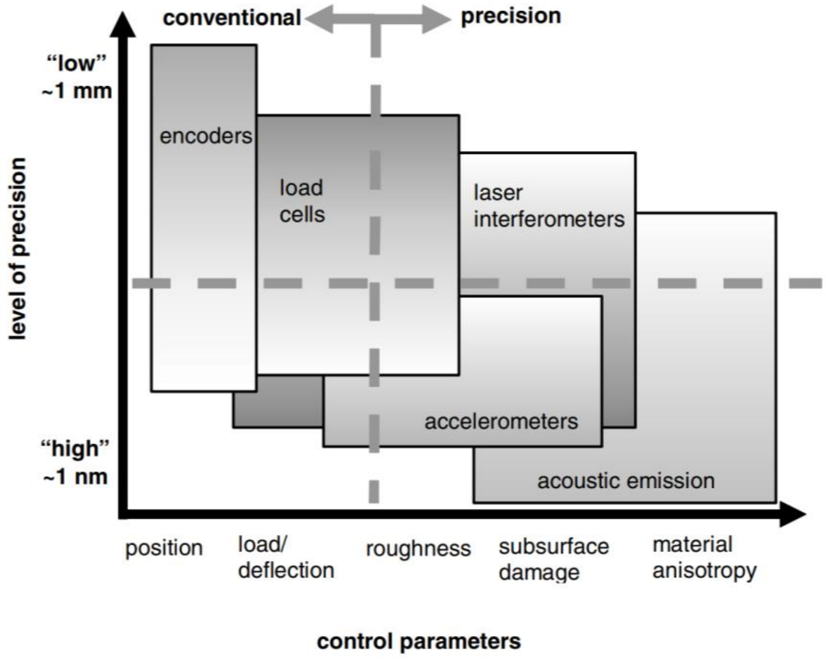


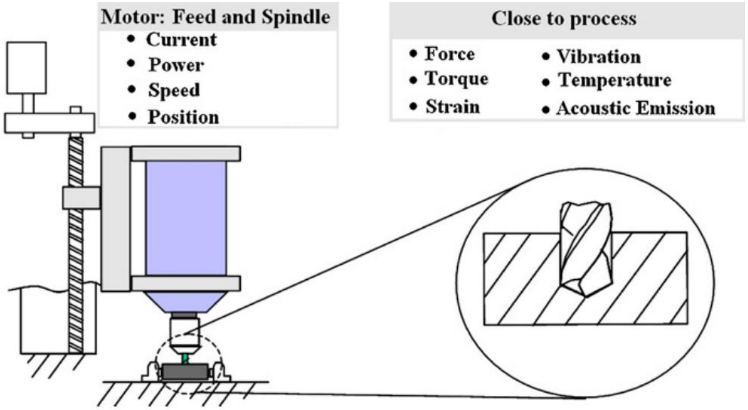
INDUSTRIAL STRATEGY

Ulhman E *et al.* (2016) *CIRP Annals* **65** 549-572

Sensors required for machine tool control

Sensor application versus level of precision and control parameters

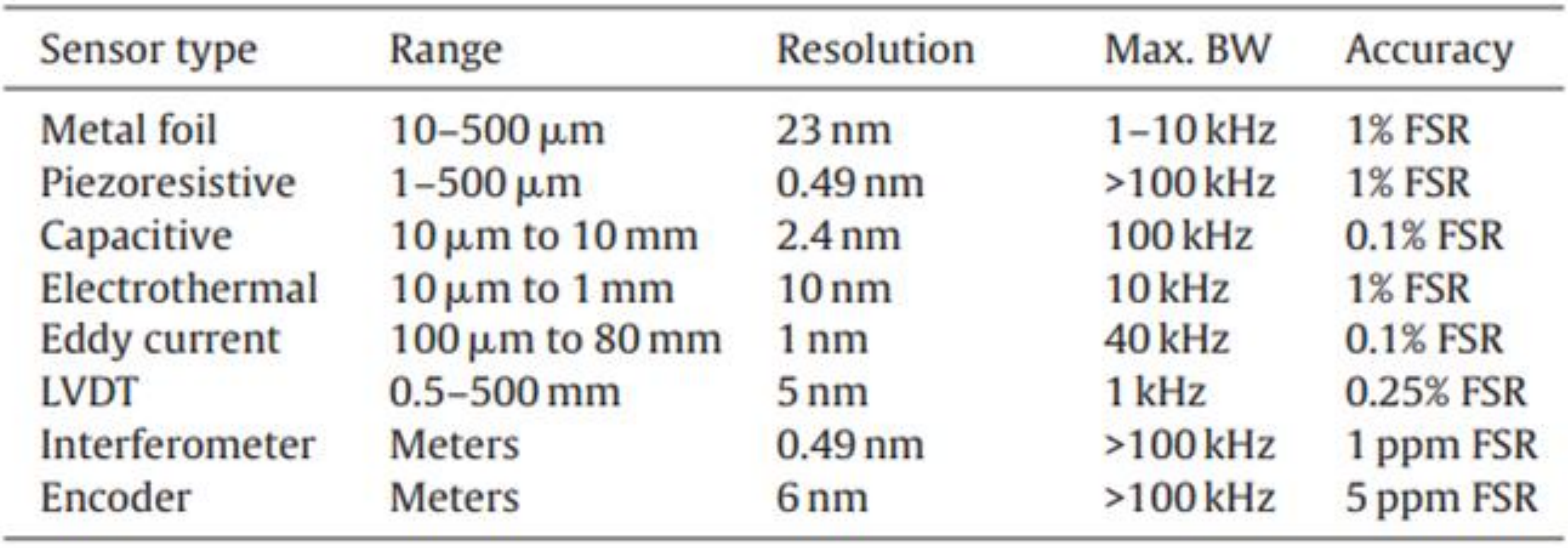




Lee DE *et al.* in *Condition Monitoring and Control for Intelligent Manufacturing* Wang L and Gao RX Springer, London (2006), 33-54

Teti R *et al.* (2010) *CIRP Annals* **59** 717-739

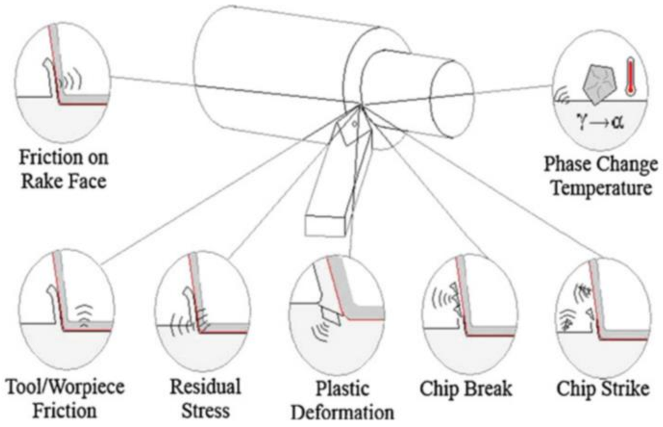
Displacement sensors



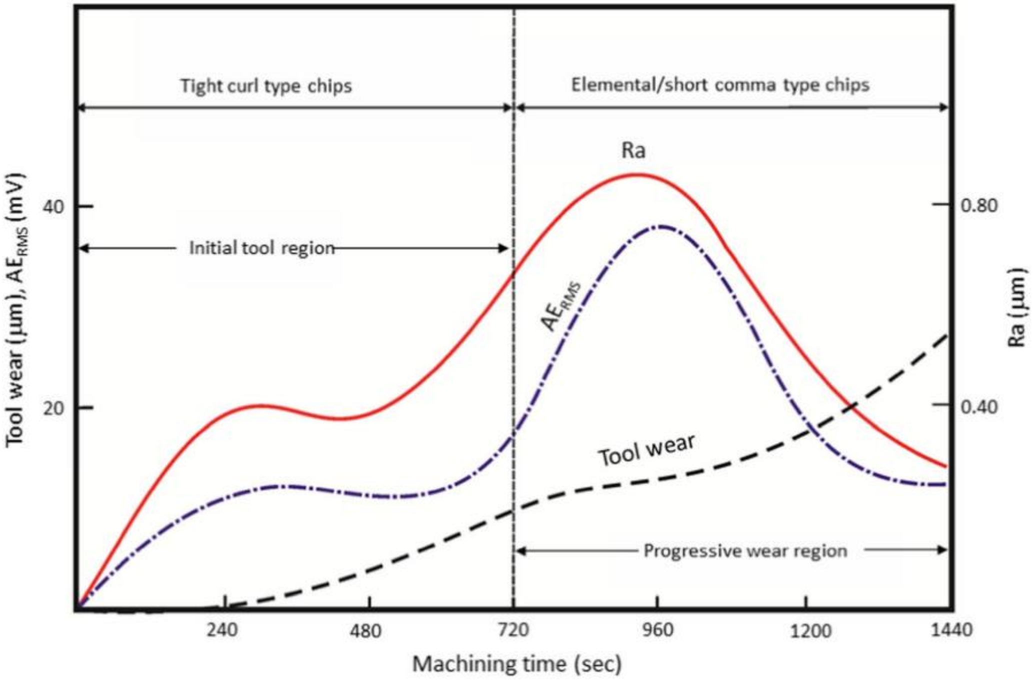
Sensor type	Range	Resolution	Max. BW	Accuracy
Metal foil	10–500 µm	23 nm	1–10 kHz	1% FSR
Piezoresistive	1–500 µm	0.49 nm	>100 kHz	1% FSR
Capacitive	10 µm to 10 mm	2.4 nm	100 kHz	0.1% FSR
Electrothermal	10 µm to 1 mm	10 nm	10 kHz	1% FSR
Eddy current	100 µm to 80 mm	1 nm	40 kHz	0.1% FSR
LVDT	0.5–500 mm	5 nm	1 kHz	0.25% FSR
Interferometer	Meters	0.49 nm	>100 kHz	1 ppm FSR
Encoder	Meters	6 nm	>100 kHz	5 ppm FSR

Flaming AJ (2010) *Sens Actua A-Phys* **190** 106-126

Acoustic emission sensors

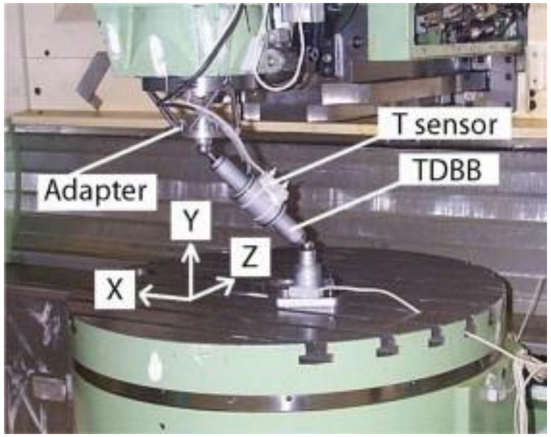


Teti R *et al.* (2010) *CIRP Annals* **59** 717-739



Kishawy *et al.* (2018) *Int J Adv Manuf Technol* **93** *(5–8)* 2275–2287

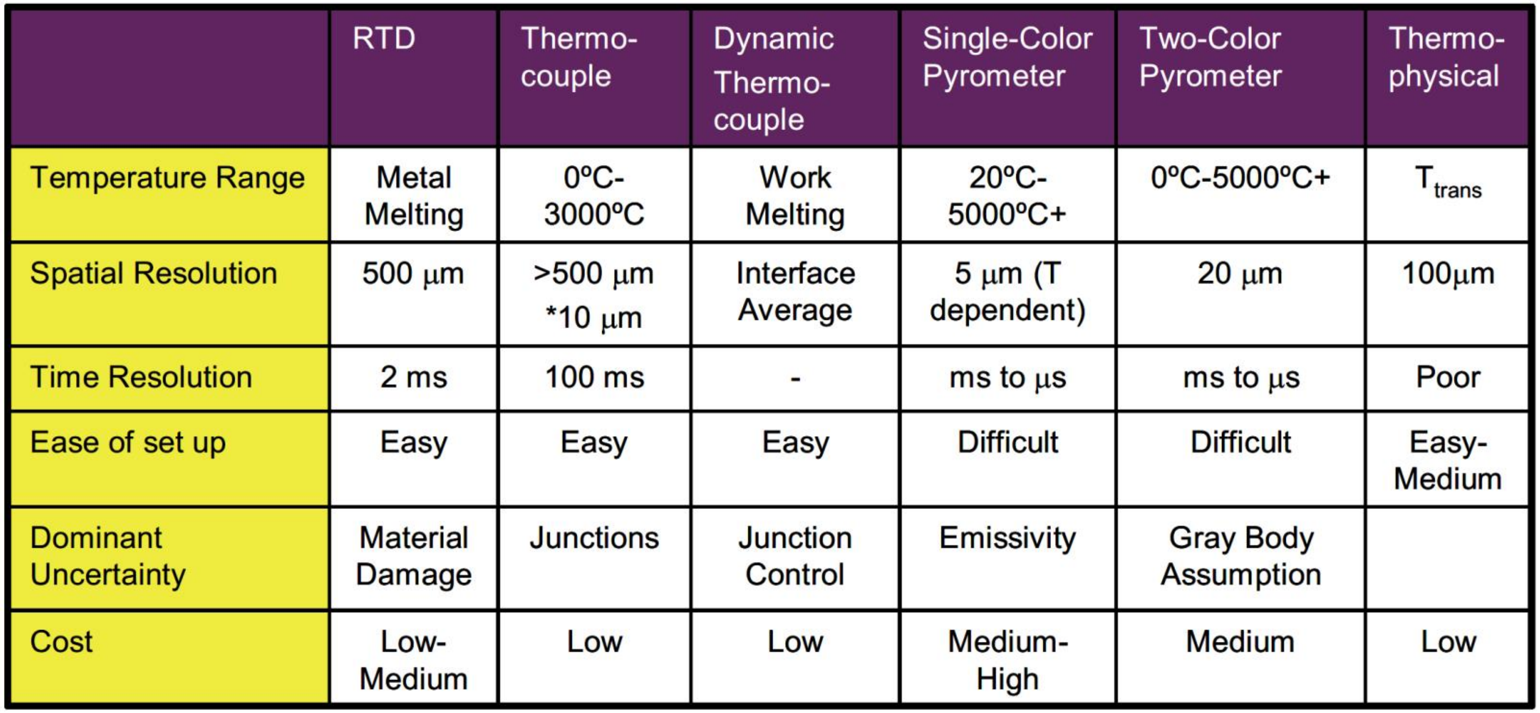
Temperature measurement



Mayr J *et al.* (2012) *CIRP Annals* **61** 771-791

Machine tools

Material removal process

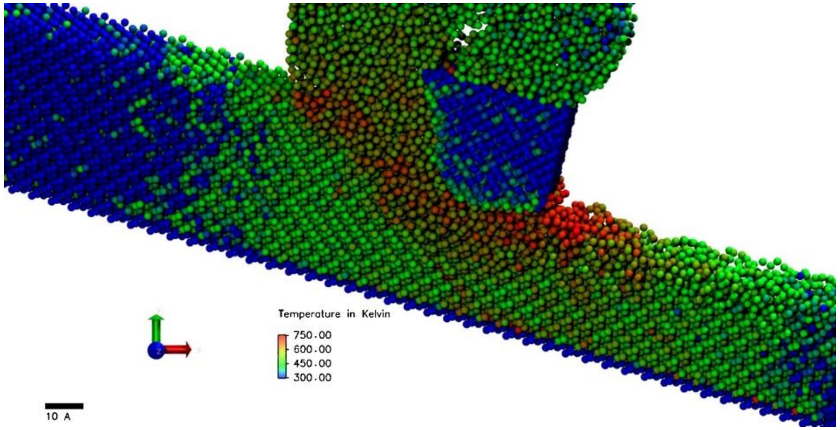


	RTD	Thermo-couple	Dynamic Thermo-couple	Single-Color Pyrometer	Two-Color Pyrometer	Thermo-physical
Temperature Range	Metal Melting	0ºC-3000ºC	Work Melting	20ºC-5000ºC+	0ºC-5000ºC+	T_{trans}
Spatial Resolution	500 μm	>500 μm *10 μm	Interface Average	5 μm (T dependent)	20 μm	100μm
Time Resolution	2 ms	100 ms	-	ms to μs	ms to μs	Poor
Ease of set up	Easy	Easy	Easy	Difficult	Difficult	Easy-Medium
Dominant Uncertainty	Material Damage	Junctions	Junction Control	Emissivity	Gray Body Assumption	
Cost	Low-Medium	Low	Low	Medium-High	Medium	Low

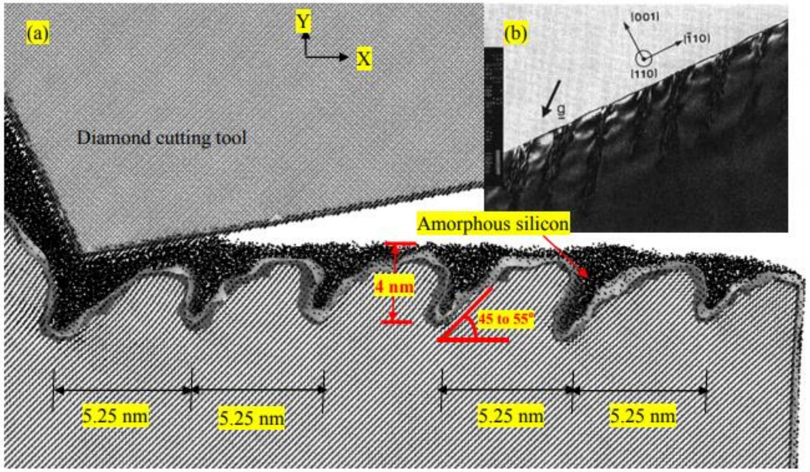
Davis MA *et al.* (2007) *CIRP Annals* **57** 581-604

Simulations results – Can we measure it?

Point of contact



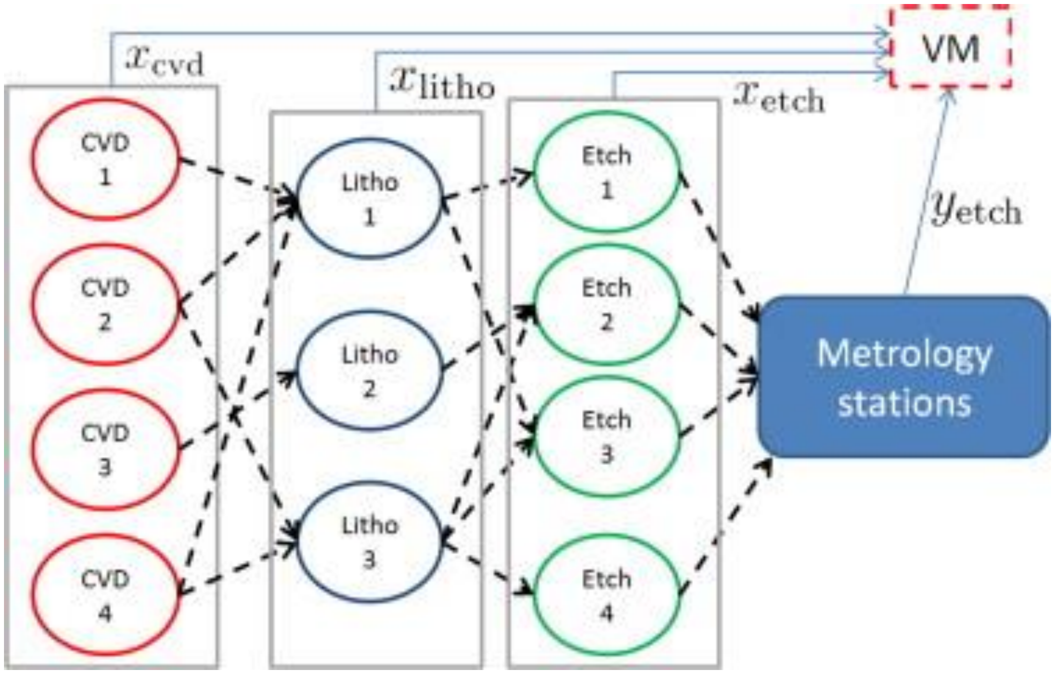
Goel S *et al.* (2012) *Wear* **284-285** 65-72



Goel S *et al.* (2016) *Acta Mat* **105** 464-478

Virtual Metrology

Reduce the cost of metrology at the end point.



Susto et al (2015) *Comp Op Res 53* 328-337

Conclusions

Must have:

- Low cost
- Wide dynamic range
- Fast
- Cooperative
- Include non-dimensional (Temperature, Stress, Strain, Acoustic Emission, Force etc)
- Able to measure at the point of machining

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