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# Integrated metrology for advanced manufacturing

**Andreas Archenti[a], Wei Gao[b], Alkan Donmez[c], Enrico Savio[d], Naruhiro Irino[e]**

[a] KTH Royal Institute of Technology, Stockholm, Sweden
[b] Tohoku University, Sendai, Japan
[c] National Institute of Standards of Technology, Gaithersburg, MD, United States
[d] University of Padua, Padua, Italy
[e] DMG MORI Co., Ltd., Nagoya, Aichi, Japan

Presenting author: A. Donmez, NIST, email: alkan.donmez@nist.gov

# Background

*"to measure what is measurable, make measurable what is not"*
*Galileo Galilei*

Motivation and objectives

- Rapid shift from **standalone** to **integrated** metrology in advanced manufacturing, driven by the need for greater efficiency and productivity.
- Keynote paper defines **integrated metrology**, exploring its characteristics, benefits, and constraints.
- Classification of **1) measurands and measuring instruments**, **2) data and its management**, **3) uncertainty and traceability** considerations.
- Addresses **current challenges** and **emerging trends**, offering **insights** for **future developments** in integrated metrology.

# Outline

1 - Introduction, classification and definitions

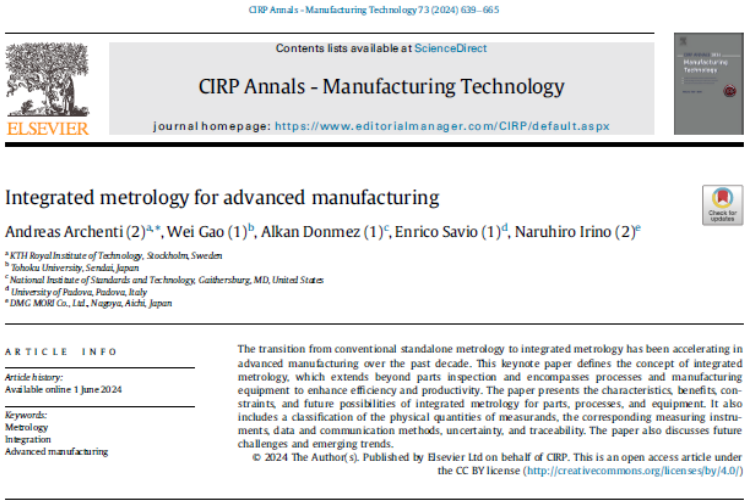
2 - Measurands and measurement instruments

3 - Data acquisition, analysis, and use

4 - Uncertainty and traceability

5 - Integrated metrology applications

6 - Summary/synthesis and future research



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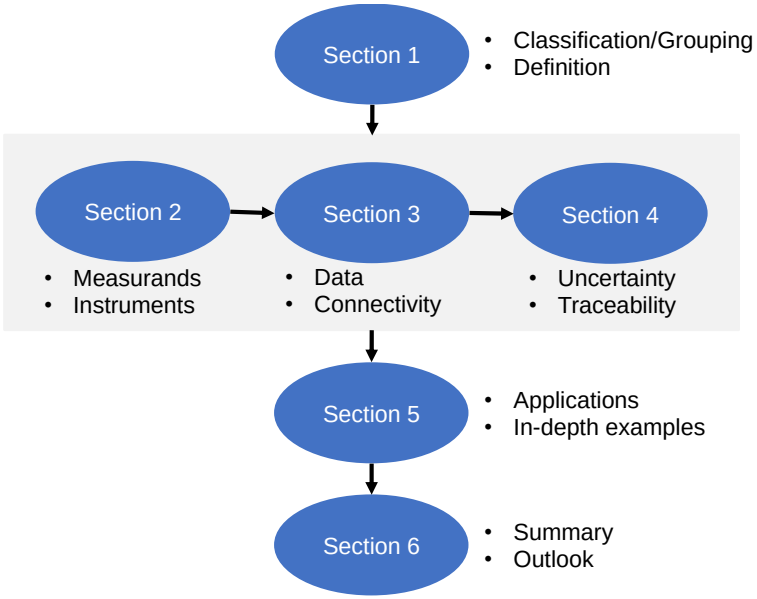
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The transition from conventional standalone metrology to integrated metrology has been accelerating in advanced manufacturing over the past decade. This keynote paper defines the concept of integrated metrology, which extends beyond parts inspection and encompasses processes and manufacturing equipment to enhance efficiency and productivity. The paper presents the characteristics, benefits, constraints, and future possibilities of integrated metrology for parts, processes, and equipment. It also includes a classification of the physical quantities of measurands, the corresponding measuring instruments, data and communication methods, uncertainty, and traceability. The paper also discusses future challenges and emerging trends.

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# 1 - Introduction, classification and definitions

**Environment**:

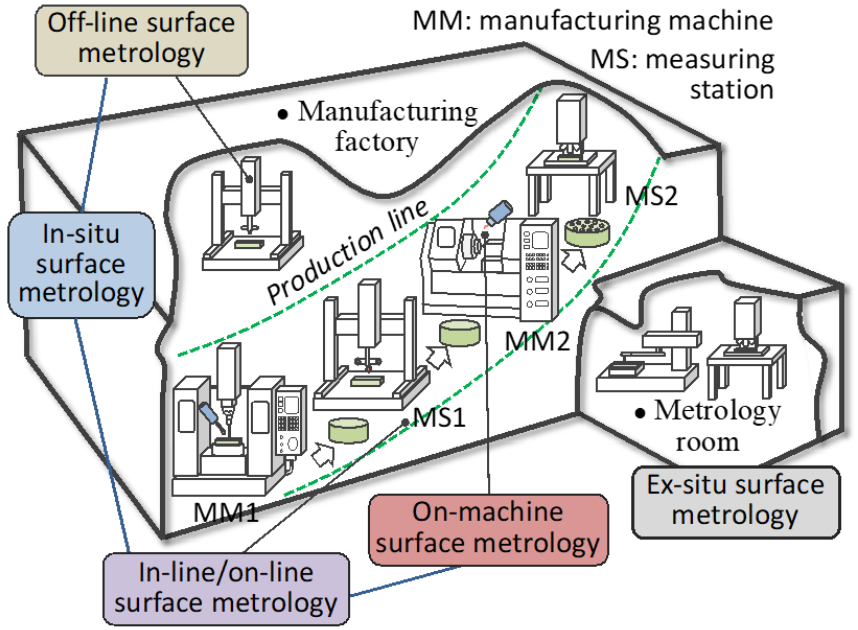
- **In-Situ**: Measurement occurs within the manufacturing environment.
  - *Example*: Infrared camera measuring workpiece temperature during production.
- **Ex-Situ**: Measurement occurs separately, with or without interaction.

**Location**:

- **On-Machine**: Within the ME's working volume or attached to its components.
  - *Example*: Shape and location measurement during machining operation.
- **Off-Machine**: Near the ME or at another process step.
  - *Example*: Inspection in a metrology room (off-line).

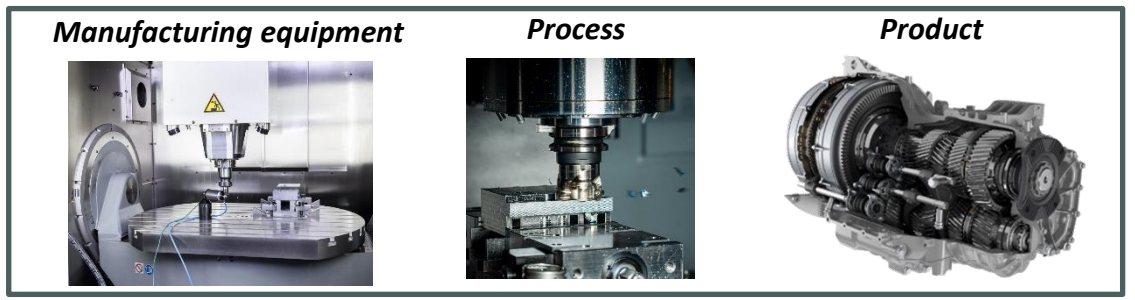
**Time**:

- **Pre-Process**: Before manufacturing.
  - *Example*: Calibration of tools before use.
- **In-Process**: During manufacturing.
  - *Example*: Temperature measurement of extrusion nozzle in additive manufacturing.
- **Post-Process**: After manufacturing.
  - *Example*: Final quality inspection after machining.




*Gao W, Haitjema H, Fang FZ, Leach RK, Cheung CF, Savio E, Linares JM (2019) On-machine and in-process surface metrology for precision*

## Scope includes:



# 1 - Introduction, classification and definitions

## Advanced Manufacturing –

*Branch of manufacturing that exploits evolving or emerging knowledge, technologies, methods and capabilities to make and/or provide new or substantially enhanced goods or services, or improve product **efficiency** or **productivity**, while ensuring environmental and social sustainability*

***New European Metrology Network for advanced manufacturing , Meas. Sci. Technol. 32 (2021) European Metrology Networks (EMNs) for advanced manufacturing***

➡ *improve product efficiency or productivity*

## Integrated metrology –

*the incorporation and exploitation of metrologically traceable data within a manufacturing system*

Note: The manufacturing system may include a machine, a process, a factory, or an enterprise

# 1 - Introduction, classification and definitions

## Importance of Metrologically Traceable Data

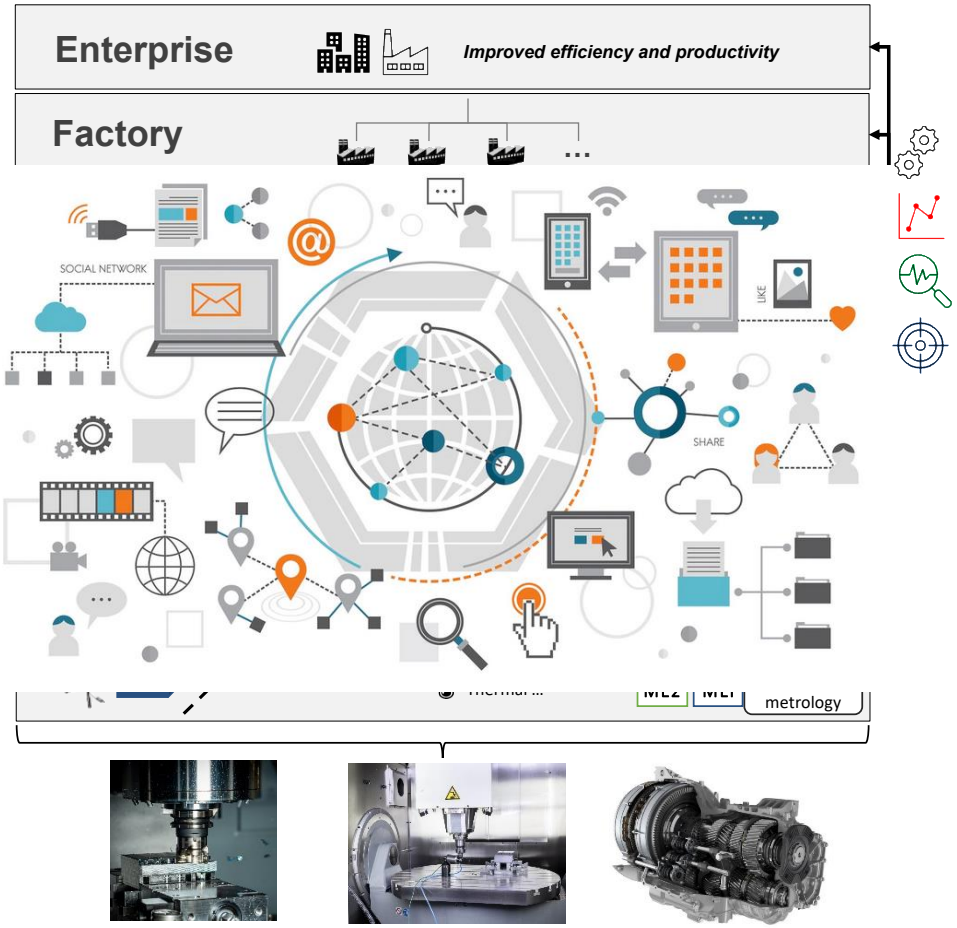
**Accessibility**: Data is freely accessible in raw or derived formats and timely available to all stakeholders.

**Versatility**: Data can include any type (e.g., quantity values, images, time series) and is transformable into quantitative product quality metrics.

**Metadata**: Includes critical information like instrument details, test and environmental conditions, measurement uncertainty, and timestamps.

**Purpose**: Ensures accurate interpretation and timely use of measurement results for product quality assessment as well as for efficient manufacturing asset management.

Process and information flow for producing final product in advanced manufacturing

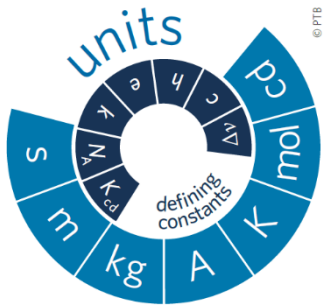


# 2 - Measurands and measurement instruments

Measurands and measuring instruments for integrated metrology

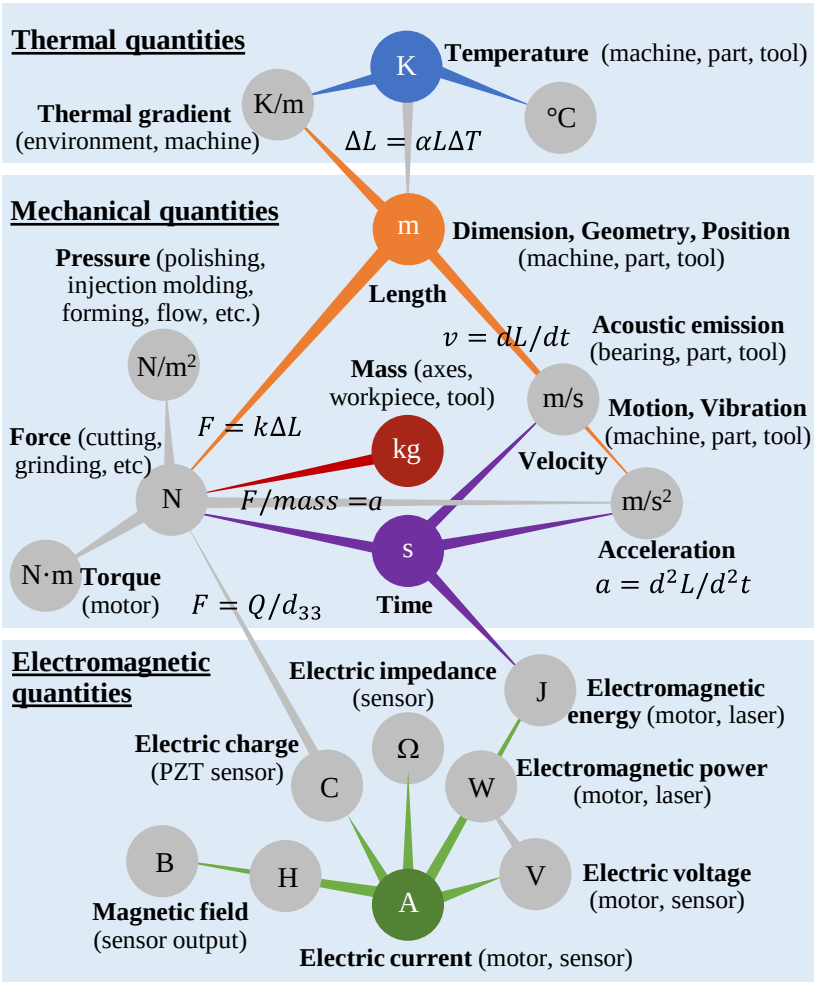
Major physical quantities directly and indirectly linked to advanced manufacturing, which can be categorized as

- **electromagnetic,**
- **mechanical, and**
- **thermal quantities.**




The quantities thermodynamic temperature (K), length (m), mass (kg), time (s), and electric current (A) are five of the seven base quantities/units of the International System of Units (SI)

*Physical quantities related to manufacturing*



# 2 - Measurands and measurement instruments

## Physical quantities of measurands related to advanced manufacturing



Machine health

- from machined component

**Manufacturing equipment**



Source: Titans of CNC

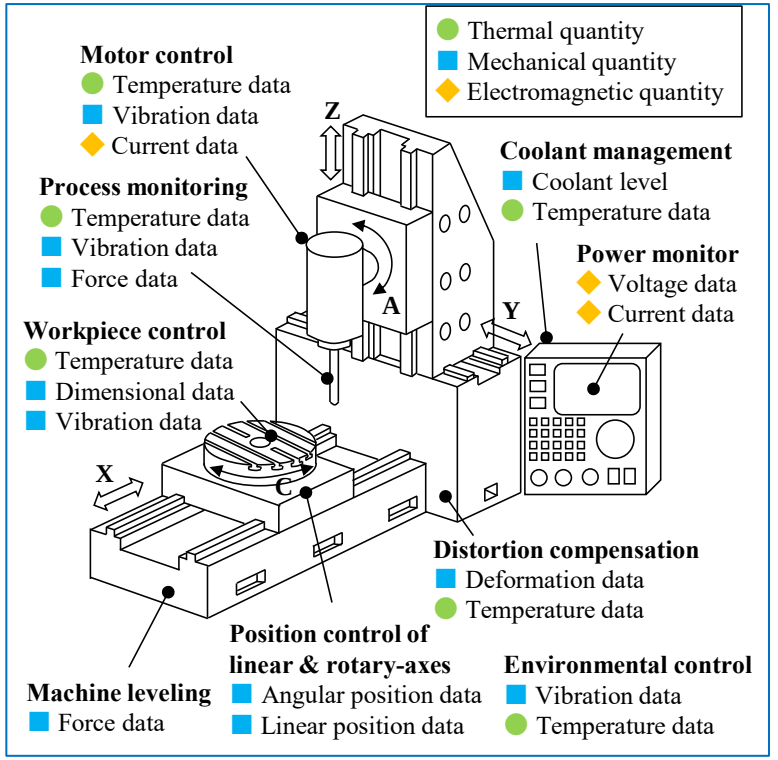


Source: Scania

Machine Capability

- from part quality

**Raw material** → **Manufactured part**

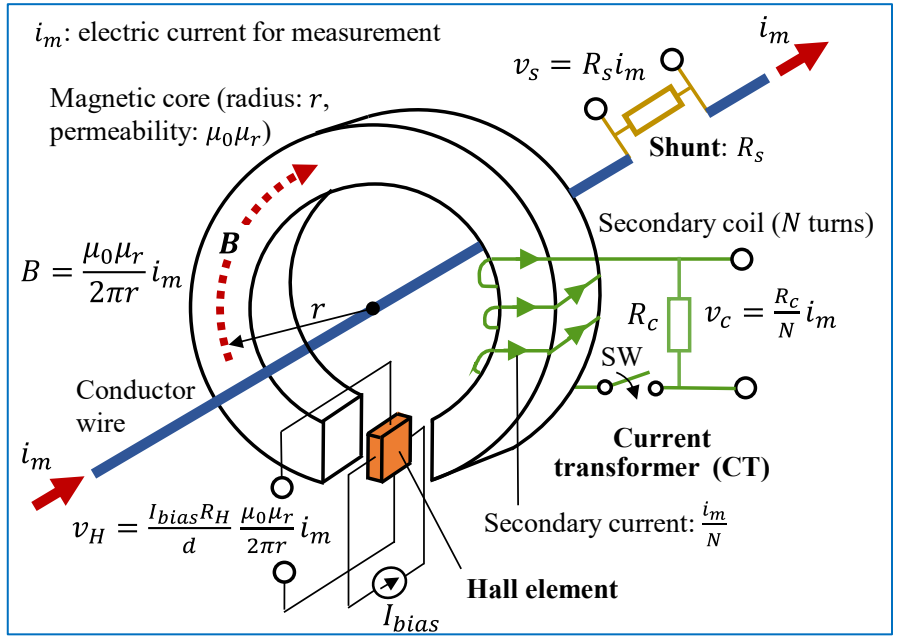



***Physical quantities as measurands employed for integrated metrology in a five-axis machine tool, modified after Koren et al***

# 2 - Measurands and measurement instruments

## Measuring instruments for electric and magnetic measurands

Electric current can be measured by using a shunt resistor, a current transformer, or a Hall sensor



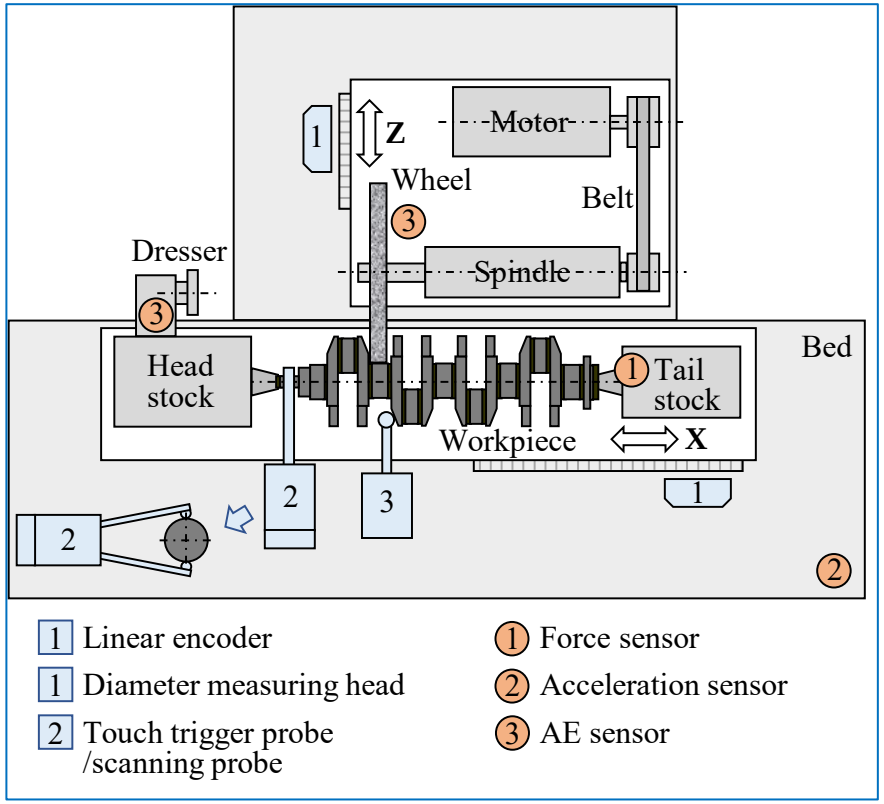

*Measurement principles of electric current by using shunt resistor, current transformer, and Hall sensor, respectively*

Features of current measurement methods

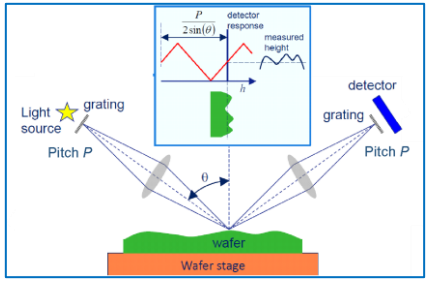
| Types | **Shunt resistor** | **Current transformer** | **Hall sensor** |
|---|---|---|---|
| Principle | Ohm's law | Faraday's law | Hall effect |
| Sensing element | Metal wire | Metal coil | Semiconductor |
| DC/AC | DC, AC | AC | DC, AC |
| Mode | Contact | Noncontact | Noncontact |

# 2 - Measurands and measurement instruments

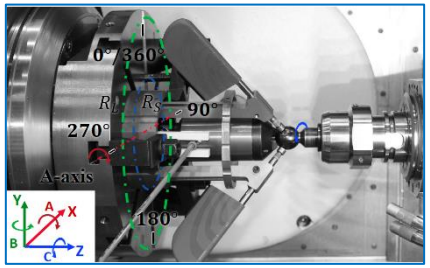
## Measuring instruments for mechanical and dimensional quantities



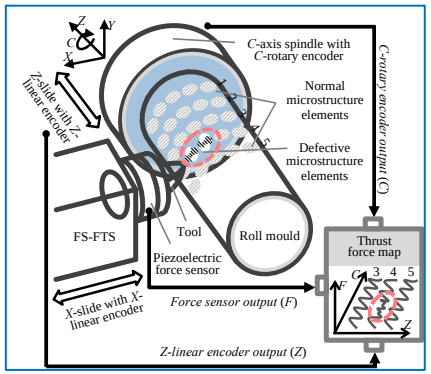

*Integrated metrology of mechanical quantities in a cylindrical grinding machine, modified after Tano*




*An optical lever sensor of wafer for integrated metrology in wafer scanner,*




*Deformation measuremnts using an LVDT probe and force inducer, Theissen, et al., Precision Engineering 2020*






*A piezoelectric force sensor embedded in a fast tool servo (FS-FTS) for detection and repair of defective microstructures, Chen et al*

***Fundamental sensor technologies for integrated metrology of dimensional quantities***

| Types | One-dimensional (1D) | Two- / three-dimensional (2D/3D) |
|---|---|---|
| Optical | Linear/rotary encoder, Length/displacement interferometer, Optical triangular sensor, Optical micrometer, Laser autocollimator | Surface encoder, Laser tracker, Laser scanner, Laser autocollimator, Machine vision, iGPS, Surface interferometer, Optical microscope, Optical scatterometer |
| Electro-magnetic | LVDT (inductance sensor), Capacitive sensor Eddy current sensor, Strain gauge | 2D Capacitive sensor, 2D inductance sensor Scanning electron microscope (SEM) Scanning probe microscope (SPM) |

***Fundamental sensor technologies for integrated metrology of dimensional quantities***

| Types | Strain gauge force sensor | Piezoelectric force sensor |
|---|---|---|
| Sensing principle | $F = \frac{ES}{k_s R}\Delta R$ (column type) | $F = \frac{Q}{d_{33}}, q = Qe^{\frac{1}{RC_d}}$ $C_d = \varepsilon_{33}\frac{S}{t}$ |
| Stiffness & resolution | Trade-off relationship (XFTC300: stiffness 47 N/μm, resolution 0.1 N, range 500 N) | High stiffness and high resolution (PCB208C02: stiffness 1050 N/μm, resolution 4 mN, range 445 N) |
| Bandwidth | DC to 1 kHz | 1 Hz to 40 kHz |

# 2 - Measurands and measurement instruments

## Measuring instruments for thermal quantities

Temperature, which is a variable determined by thermal motion of atoms and molecules

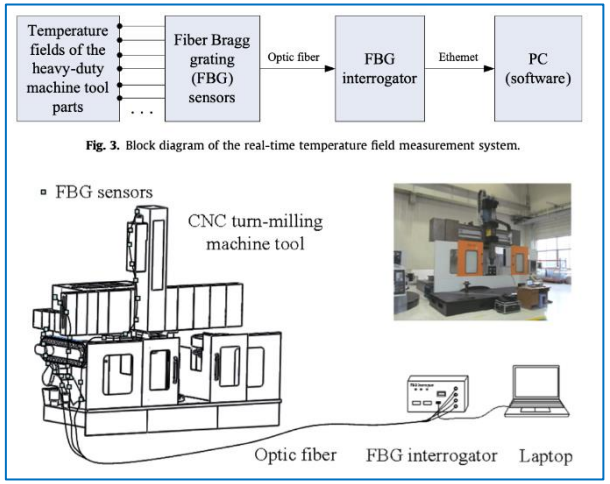
**Contact-Based Sensors:**

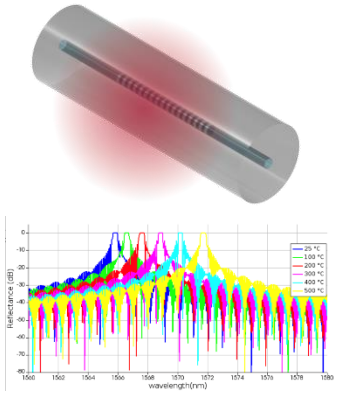
- RTDs & Thermocouples: Common for contact-type temperature measurements in equipment and parts.
- Fiber Bragg Grating (FBG): Measures temperature by detecting changes in the refractive index and shift in Bragg wavelength.

**Non-Contact Sensors:**

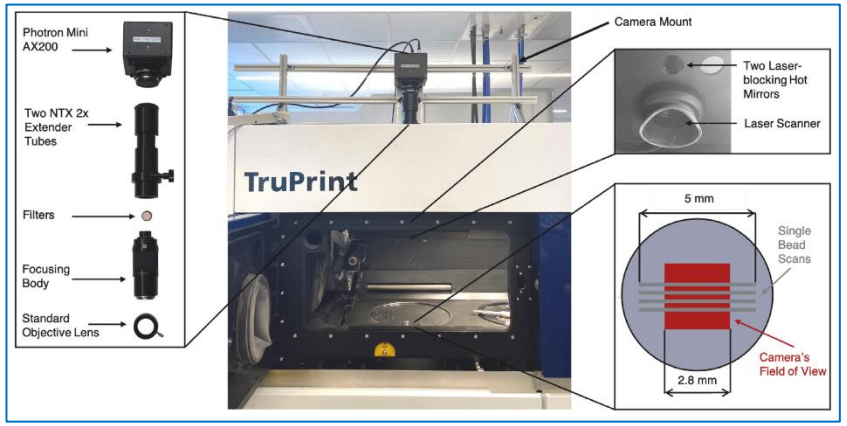
- Infrared (IR) Thermal Imaging Cameras: Capture temperature variations without contact.
- Pyrometers: Measure temperature from a distance using infrared radiation

***Real-time measurement of temperature field in heavy-duty machine tools using fiber Bragg grating sensors and analysis of thermal shift errors , Huang et al***



***Fiber Bragg Grating Temperature Sensor, Ansys Optics***




***High-resolution melt pool thermal imaging for metals additive manufacturing using the two-color method with a color camera, Myers et al***

# 3 - Data acquisition, analysis, and use

Advanced manufacturing systems generate significant amounts of data in all stages of manufacturing processes, from design to delivery of products.

Numerous physical quantities need to be measured to control manufacturing processes and assess part quality.

Efficient acquisition and processing of measurement data, as well as timely communicating such data across the manufacturing enterprise are key features of integrated metrology.

- Data acquisition/classification
- Data analysis / processing
- Data exchange/communication
- Use of metrology data/information for decision making

# 3 - Data acquisition, analysis, and use

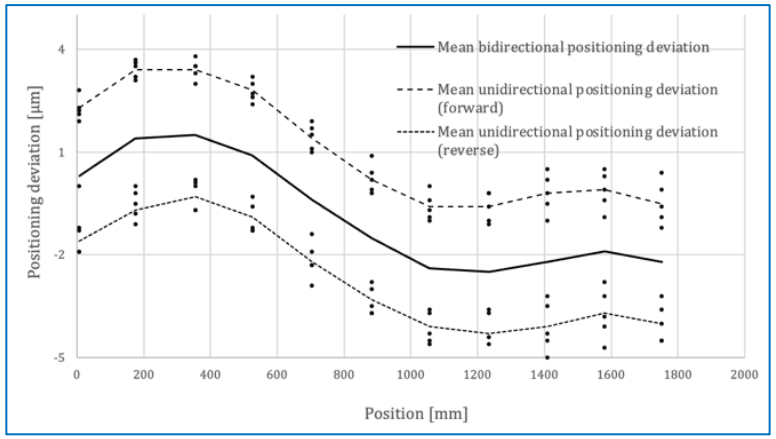
## Data acquisition/classification

## Spatial Density

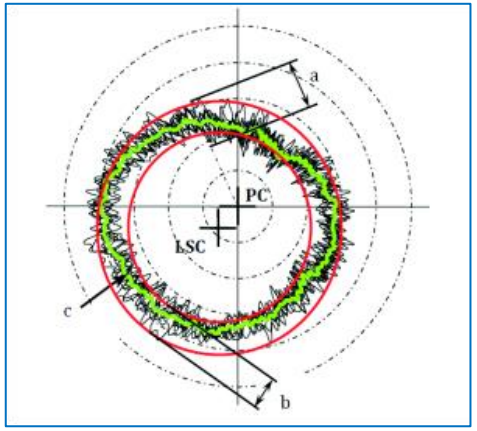
- Low (e.g., part dimensions, machine tool positioning error)
- Medium (e.g., part form)
- High (e.g., part surface finish, part XCT images, machine spindle errors)

## Temporal Density

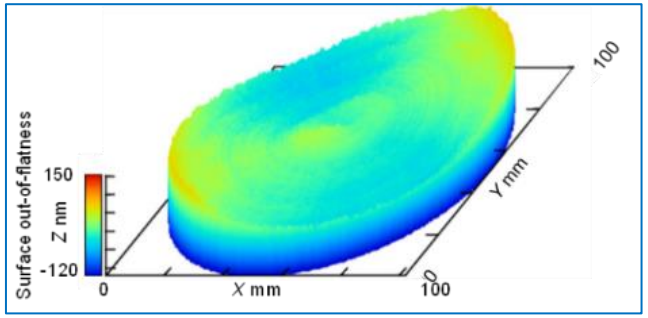
- Static (e.g., finished part dimensions)
- Quasi-static (e.g., machine tool thermal errors)
- Dynamic (e.g., machine vibrations, cutting forces, cooling rates in additive manufacturing)




*An example the data representation of machine tool axis positioning error , ISO*




*Data representation of machine tool spindle asynchronous and synchronous error motions in polar coordinates, ISO*




*An example of the data representation of surface out-of-flatness of a diamond turned part , Gao et al*

# 3 - Data acquisition, analysis, and use

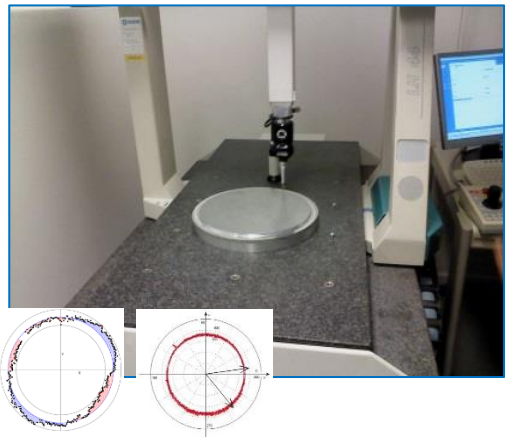
## Data analysis/processing

***Direct measurement data*** fully representing the value of the measurand without further processing (e.g., dimensional measurement by CMM)

***Indirect measurement data*** requiring data models and processing to obtain reduce measurands and extract features, also called as ***Computational Metrology*** (e.g., flatness of a surface, XCT tomographic reconstruction)

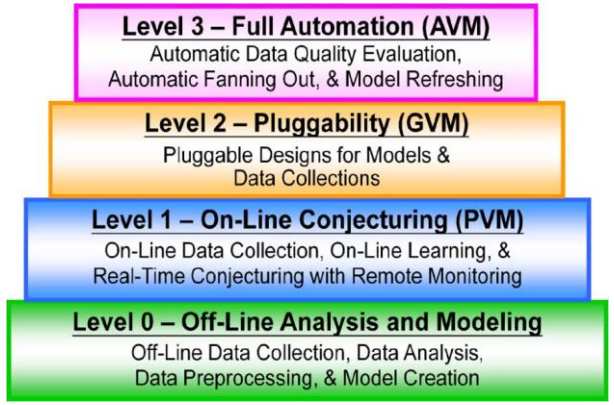
**Hybrid measurement data** combining/processing data from two or more types of measuring instruments to measure the same measurand for the purposes of improving measurement performance (e.g., utilizing edge and cloud computing)

***Virtual Metrology*** estimating the values of measurands by using manufacturing equipment/process parameters and other available data (and models) associated with the manufacturing process.



*Direct measurement using a CMM, provides coordinate values for each point inspected*

**Virtual metrology:**




*Automation levels of virtual metrology systems, (semiconductor manufacturing) Fan-Tien Cheng*

# 3 - Data acquisition, analysis, and use

Data exchange/communication

For efficient archiving, managing, and sharing of metrology data within the advanced manufacturing systems, information models associated with the measurements are needed:

- measurement procedure, measuring instrument and setup, measurement uncertainty, environmental and other conditions under which the measurements are conducted. **[*EMPIR – SmartCom Project, 2019*]**

**FAIR principles:** Findable, Accessible, Interoperable, and Reusable—must be applied to ensure data is easily located, securely accessed, compatible with various tools, and reusable for different purposes. **[*The FAIR Guiding Principles for scientific data management and stewardship, 2016*]**

**Standard protocols:** communication with sensors and manufacturing equipment **[*OPC UA* (2008)** and ***MTConnect* (2018)]**.

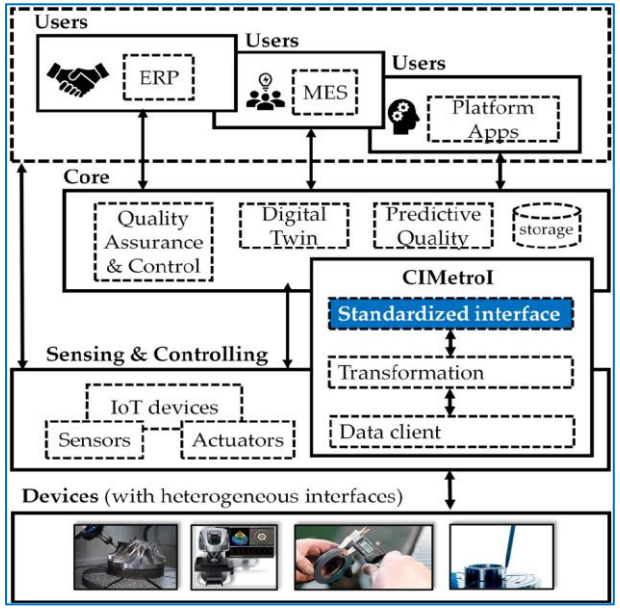
**Quality Information Framework (QIF):** An integrated model for manufacturing quality information including a common communication language and data structures to communicate information about workpiece quality and enable software development for communication of manufacturing quality data [***ISO 23952:2020***]

# 3 - Data acquisition, analysis, and use

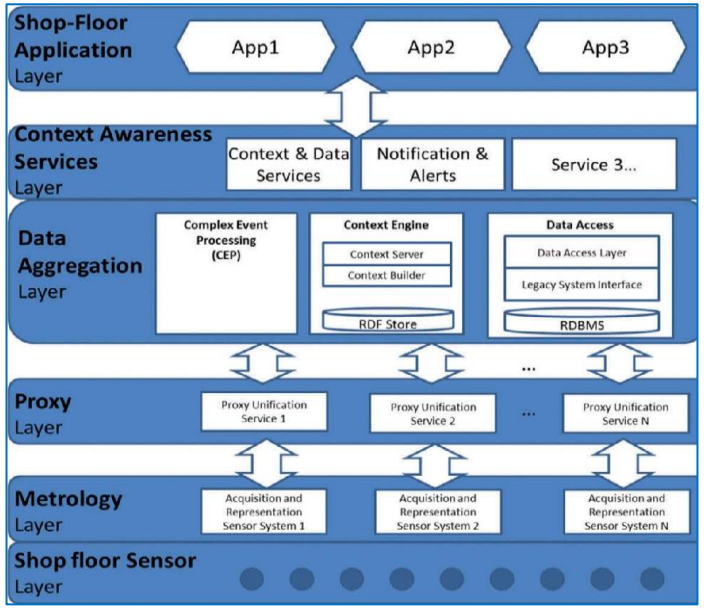
## Use of metrology data/information for decision making

Easy access to metrology data across all levels of a manufacturing enterprise ➡ timely, effective decision-making for efficient, high-quality production

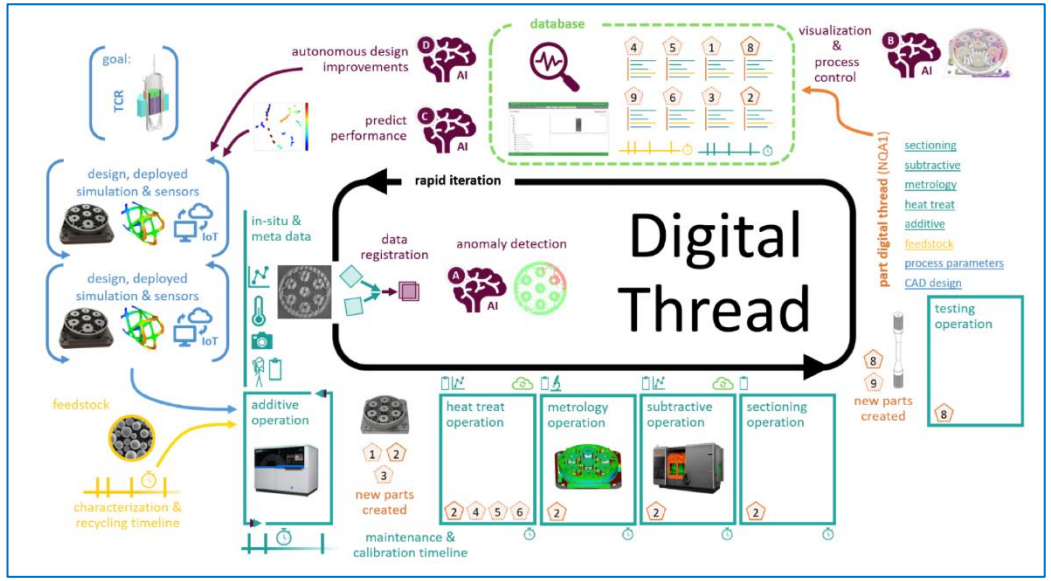
Information frameworks are necessary to link disparate sources of metrology data stored in different locations and contexts for process control, planning, and product qualification




*Overview of the architecture for the CIMetroI, Sousa et al*




*Architecture of the context-aware information handling and distribution system in manufacturing, Alexopoulos et al*




*A graphical representation of the information contained within a digital thread of an additively manufactured component, Huning et al*

# 4 - Uncertainty and traceability

To address measurement uncertainty in integrated metrology, **error sources** must be identified, **systematic effects** potentially compensated, and **overall uncertainty** quantified.
In harsh on-machine or in-line environments, additional uncertainty may arise due to increased error contributors and magnitudes, making certain effects more significant compared to controlled laboratory conditions.

- Electro-Magnetic measurements
- Mechanical measurements
- Thermal measurements
- Metrological traceability for integrated metrology

# 4 - Uncertainty and traceability

Electro-Magnetic measurements sources of uncertainty

i. **Electromagnetic interference** from nearby manufacturing equipment, etc.
ii. **Temperature** and influences on resistance, capacitance, and other electrical properties.
iii. **Humidity** can affect insulation resistance, introduce leakage currents, and cause short circuits
iv. **Vibrations** and mechanical stresses can impact electrical connections, lead to contact resistances, and affect the stability of measurement setups.
v. **Dust** and other **contaminants** can cause insulation breakdown, increase contact resistance, and interfere with signal transmission

# 4 - Uncertainty and traceability

## Mechanical measurements

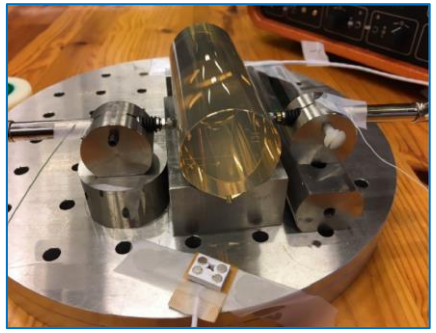
Mechanical quantities, particularly **length**, are crucial in manufacturing because they directly impact the **dimensions**, **geometry**, and functional performance of products.

Sources of uncertainty:

- Instrument alignment
- Thermal effects
- Vibrations
- Extended measurement loops

Uncertainty reduction by

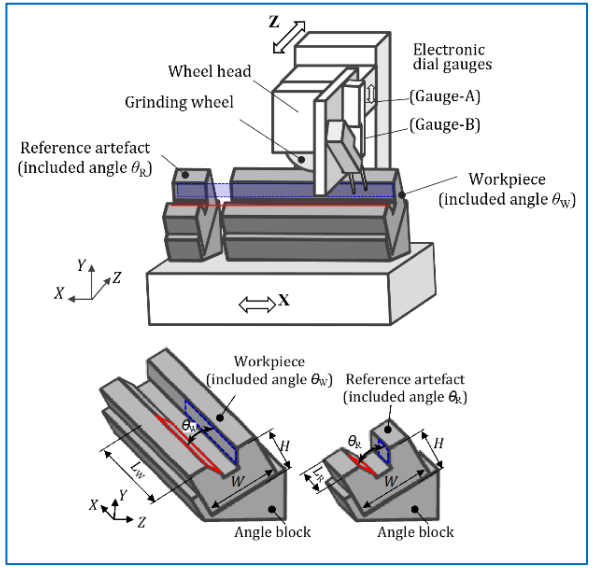
- Use of calibrated master workpieces
- Simultaneous temperature measurements to compensate for thermal effects
- Reduced measurement loops



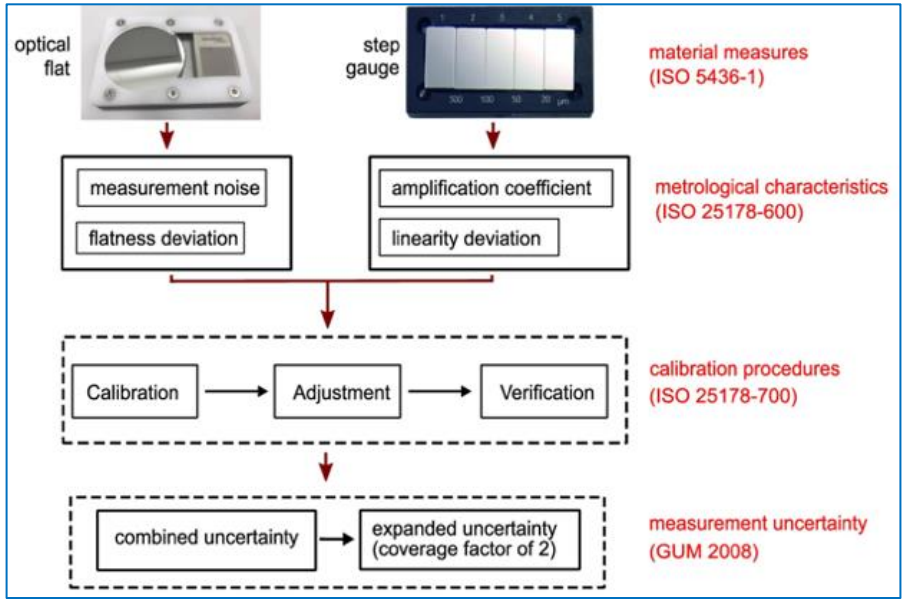
*Zero-setting of the inductive probes using a calibrated Zerodur reference cylinder , De Chiffre et al*



*Calibrated master shaft for comparative measurement , Marposs*




*Comparative angle measurement with a reference artifact for compensation of thermal effects, Shimizu et al*




*Overview of the calibration process for an on-machine chromatic confocal sensor integrated into a micro-EDM machine tool , Ye et al*

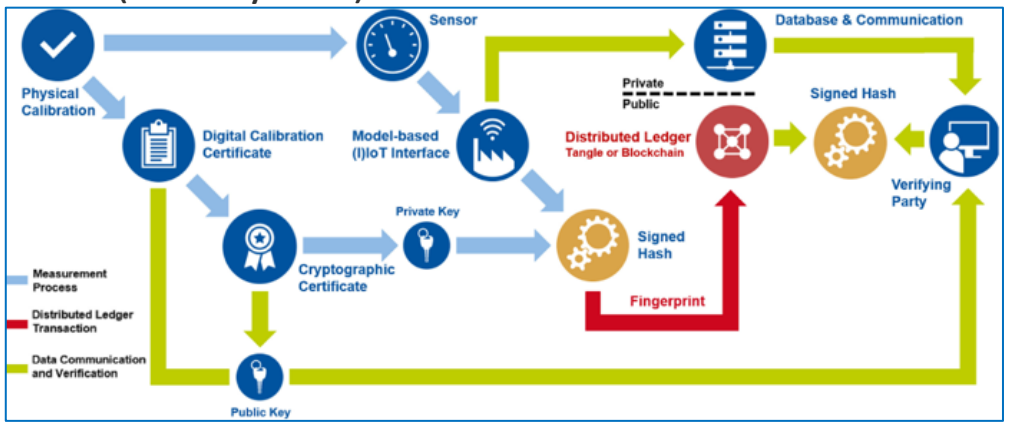
# 4 - Uncertainty and traceability

## Metrological traceability for integrated metrology

Embedded sensors in machinery face drift due to harsh environments and limited access for traditional calibration methods. Data validity and metrological traceability are key requirements.

**Solutions**: redundant systems, eg., self-calibration, remote techniques, and predictive maintenance, with calibration planned during downtime to minimize disruption.

**Documentation**: calibration history, hierarchy, and other relevant details, with development of XML-based digital calibration certificates (DCC by PTB)




*Example of traceability relating a measurement record acquired by a traceable sensor to a signed hash as fingerprint in a distributed ledger, Peterek M and Montavon B*

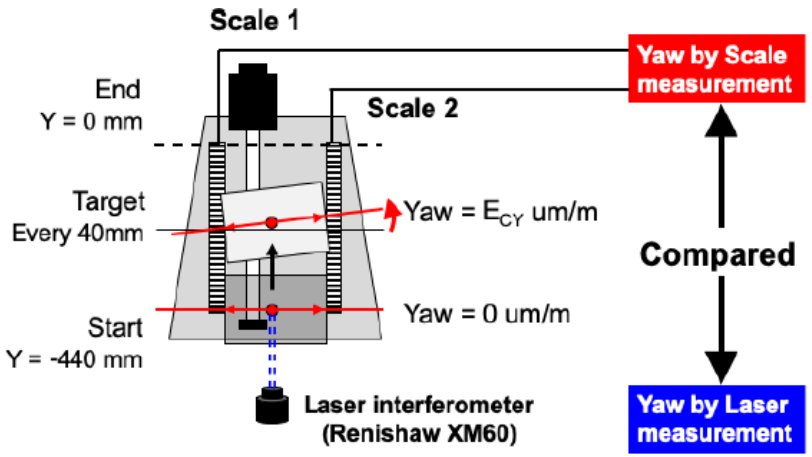
Example using international secure data exchange standards **X.509** and **IOTA**:

- Physical calibration of sensor
- Digital validation certificate
- Asymmetric cryptographic with a public key
- Distributed IoT-Protocol

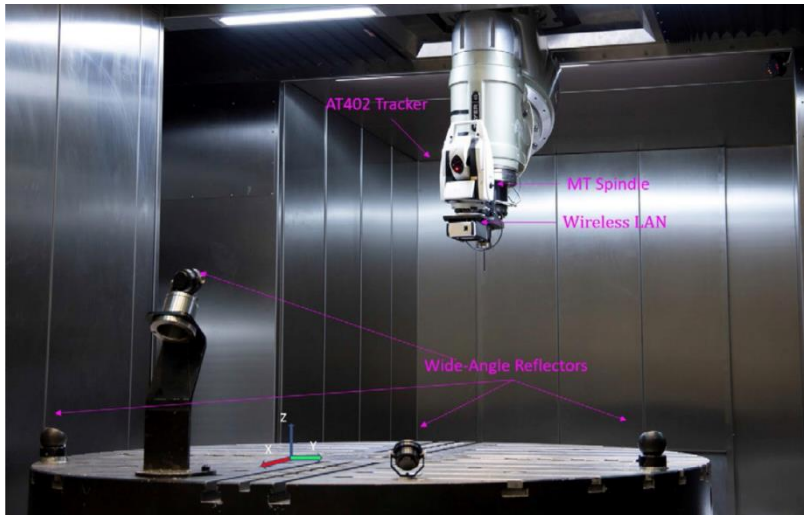
# 5 - Integrated metrology applications

Manufacturing equipment

A relevant application of integrated metrology based on dimensional quantities is error compensation of machine tool geometry.
Error compensation is a methodology for removing geometrical errors by adjusting the motion of the machine.




*The verification of the yaw measurement principle by comparing the measurement with a laser measurement. Comparison of the measurement value of the linear scale system and that of the laser interferometer , Kidani (2022)*




*Machine Tool Integrated Multilateration (MIIM) approach, Egana et al (2021)*

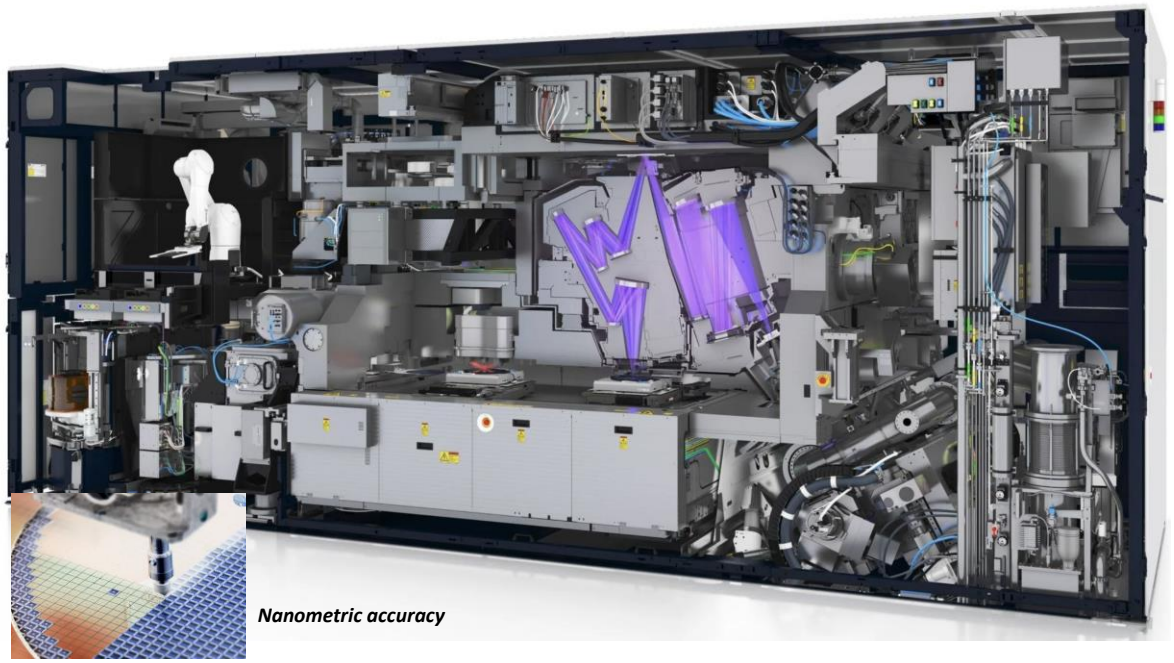
# 5 - Integrated metrology applications

Production processes - Lithography

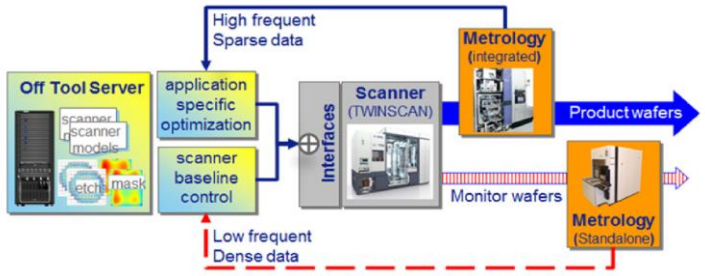
Semiconductor manufacturing: ASML Holistic Lithography approach

Integrated metrology is playing a crucial role

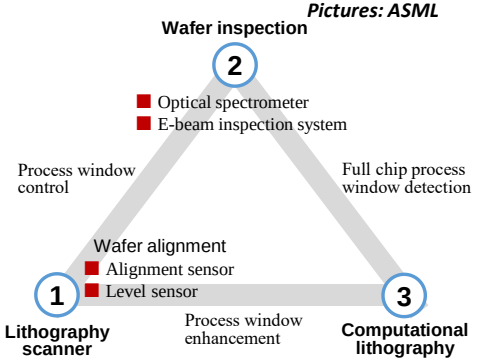
The ASML scanner is composed of two stages: an exposure stage and a metrology stage
100 % of wafers are measured on the metrology stage before being moved to the exposure stage for exposure




*Pictures: ASML*




*Integrated and standalone metrology in lithography, Muller (2018)*

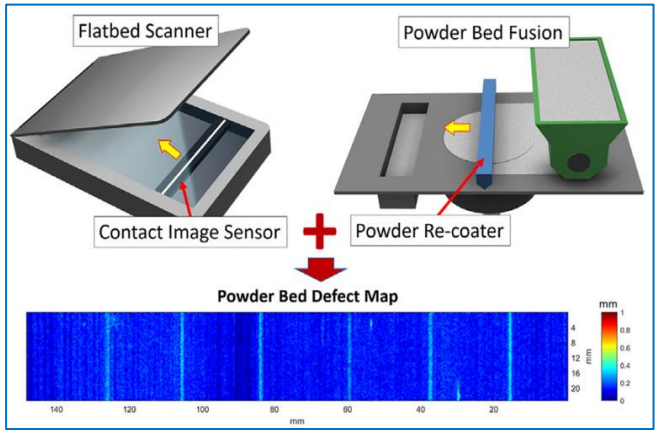



*Metrology in the context of holistic Lithography, Ottens (2017)*

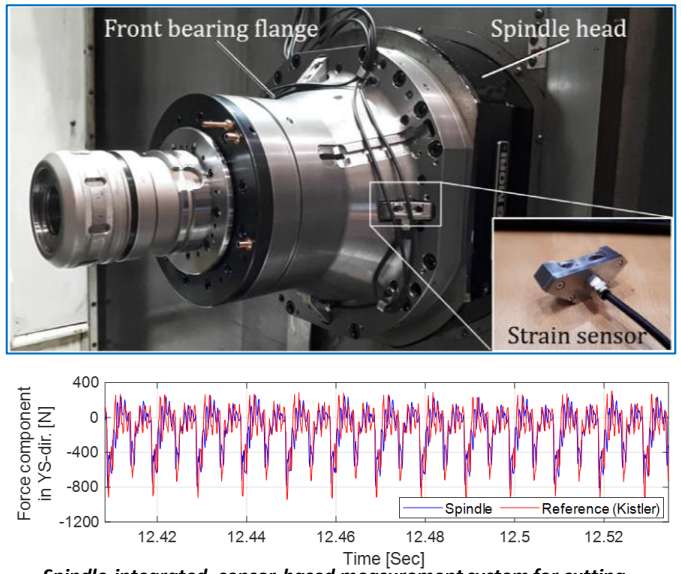
# 5 - Integrated metrology applications

## Production processes

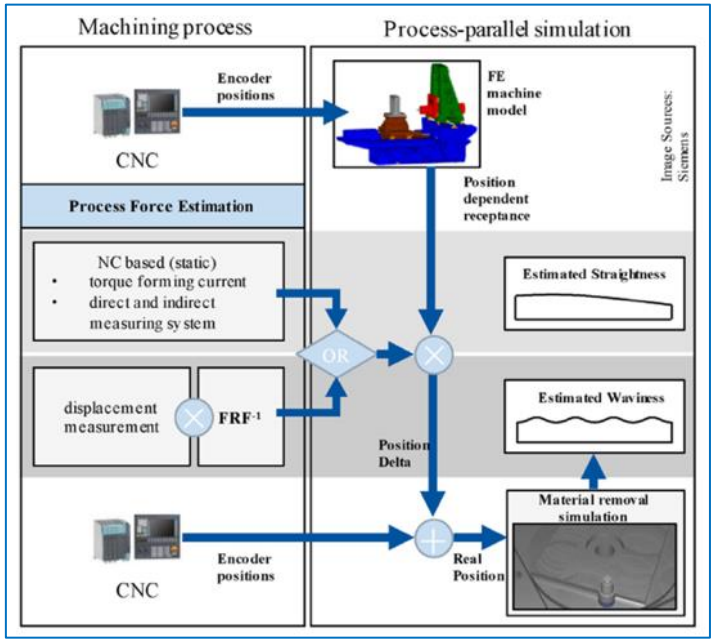
## Integrated automatic measurement and compensation system



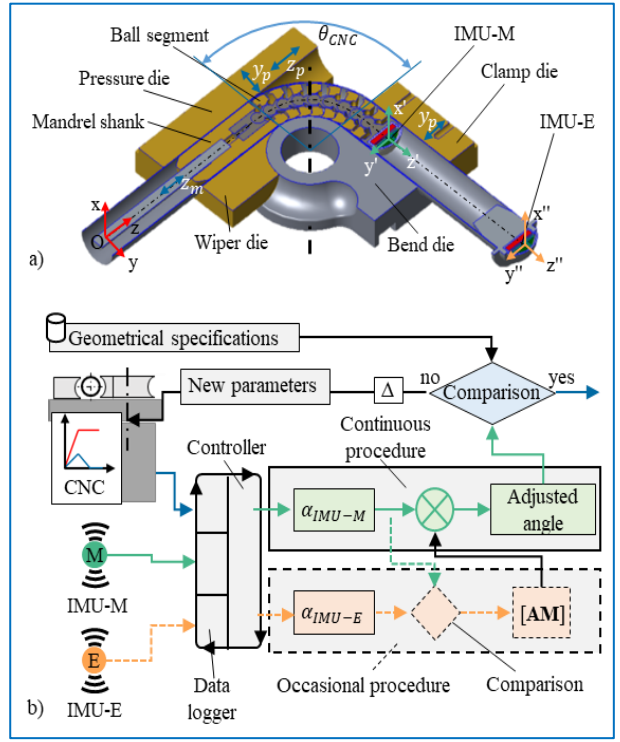

*Concept of the experimental setup and distance map after correction of raw scan data, Le Tan Phuc (2019)*




*Spindle-integrated, sensor-based measurement system for cutting forces, Boujnah (2022)*



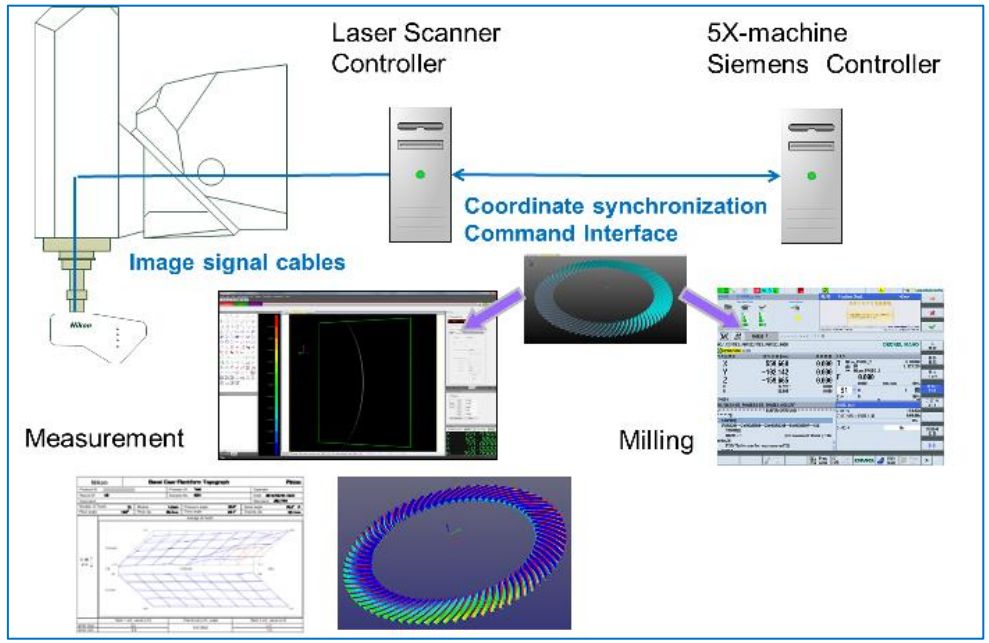

*Estimation of the virtual workpiece quality by the use of a spindle-integrated process force measurement, Brecher (2019)*



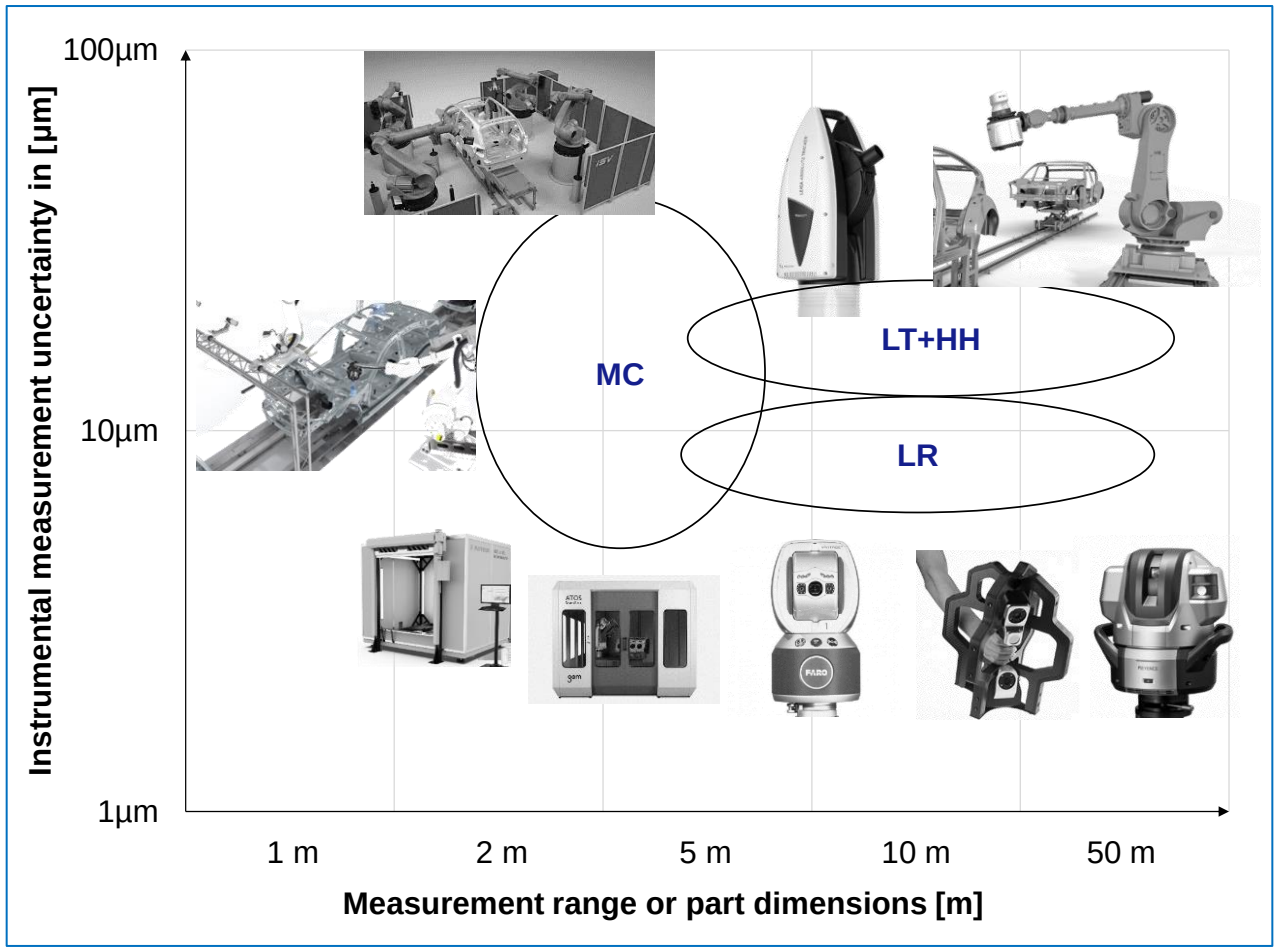

*Schematic of the IMU sensors embedded on a tube bending machine Ghiotti (2021)*

# 5 - Integrated metrology applications

## Product




*On-machine measurement system for bevel gear machining, Kanto et al (2017)*




*Overview measurement instruments integration in production line for part metrology: i) Laser Tracker and Hand-Held (LT+HH) ii) LR laser radar, i.e., laser tracker without any target, iii) Measurement cell type I and II*

# 5 - Integrated metrology applications

Product

In the aerospace industry, 100 % part inspection and control have been longstanding practices and the industry is moving towards more use of integrated and automated dimensional metrology solutions

- A recent study proposes a framework for managing traceable, interoperable 3D models and measurement data using digital models and threads for optimizing automated laser radar systems across multiple factories, Lindqvist et al.

- It emphasizes the ability to program metrology systems offline globally and execute measurement programs online in different locations, ensuring full traceability of models and programs.

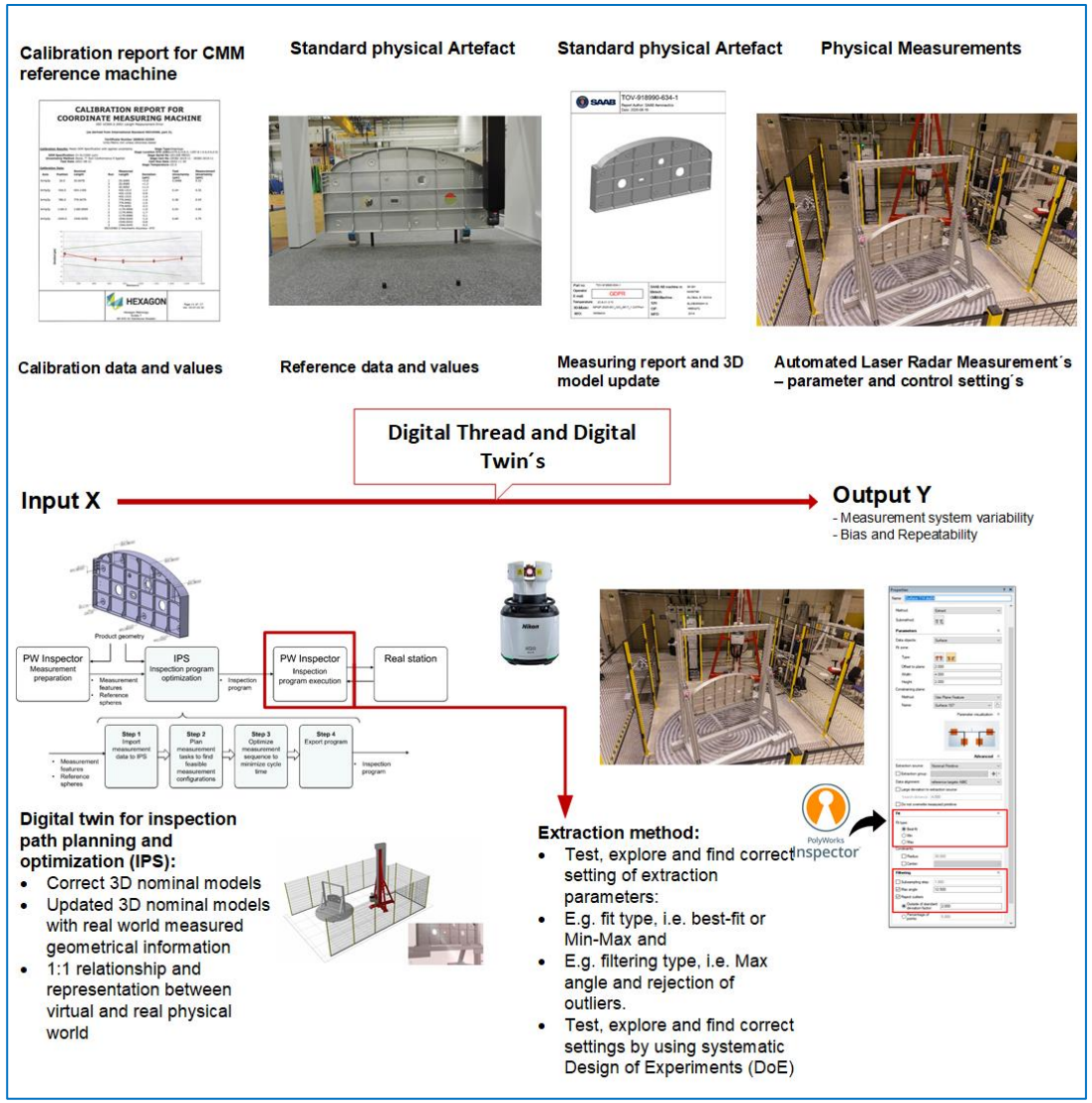



*Illustration showing traceable metrology and measurements in integrated and automated metrology system concepts using a Laser Radar (by courtesy of Saab AB).*

# 6 - Summary

In the era of digitalization, integrated metrology serves as a key enabler of advanced manufacturing, facilitating improved quality control, process optimization, and cross-company collaboration.

Integrated metrology plays a pivotal role in advancing manufacturing systems by ensuring product quality, resource efficiency, closed-loop operations, and data-driven timely decision-making.

Traceable measurements and inspections, combined with digital tools and uncertainty management, are instrumental in achieving above goals

# 6 - Summary

Identified Research gap / outlook

The transition from conventional standalone metrology to integrated metrology has been accelerating in advanced manufacturing over the past decade

- The integrated approach extends beyond **parts inspection**, encompassing **processes** and **manufacturing equipment** for increased efficiency and productivity
- For integrated metrology applications, **standardized platforms** that can share and exchange measurement data will become increasingly important for quality assurance and production optimization
- Clear communication of metrology data/information requires **data dictionaries**, **consistent data** and **metadata structures** and formats, and **communication protocols**

# 6 - Summary

Future work - identified Research gap / outlook / roadmap

- **Sensors and measuring instruments** include the development of low-cost, robust, light-weight and compact sensors, such as optical sensors based on mass-produced metalenses
- **Low energy and wireless communication networks (5/6G)**, can provide significant benefits to manufacturing metrology processes
- **Metrology data** for decision making as qualification and quality assurance of manufactured parts are arising rapidly with the advent of digital manufacturing technologies
- Making **more use** of the collected metrology data, increase the robustness

# 6 - Summary

Identified Research gap / outlook / roadmap

- Combining knowledgebase with data driven analytics including **AI/machine learning tools** for fast recognition of deviations
- In relation to measurement uncertainty, further work is needed to develop reliable and validated (i.e. traceable) **digital twins** of the integrated metrology systems, particularly when dealing with optical measuring systems and harsh environmental conditions
- Need for **standardisation**. Digital calibration certificates (DCC) develop universal exchange formats ensuring both data validity along digital processing chains and metrological traceability at different levels

# Thank you for your kind attention!





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