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EPSRC
Engineering and Physical Sciences
Research Council

The Future
Metrology
Hub

University of
HUDDERSFIELD

Process control
State of the Art review

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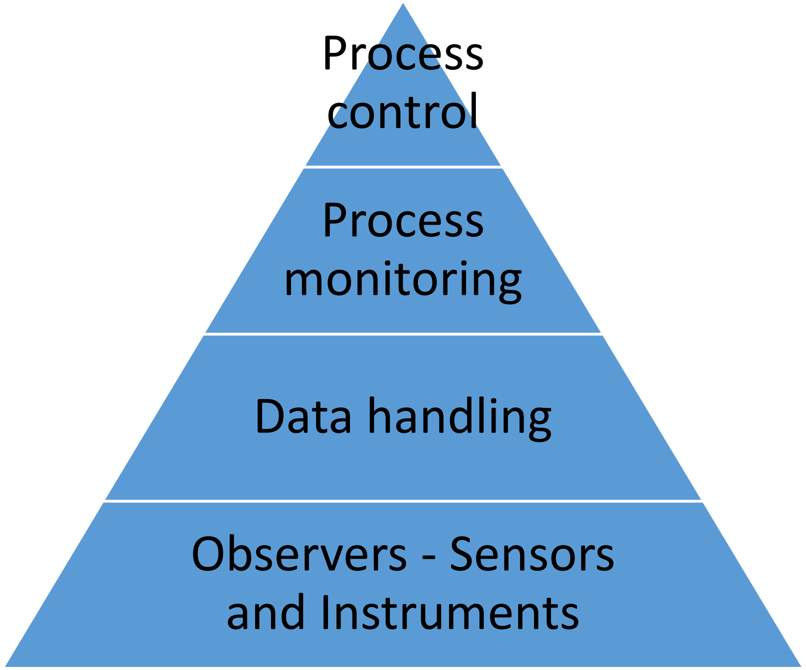
Loughborough University

NPL National Physical Laboratory

The University Of Sheffield.

Process control - State of the Art review

The need for control



Process control

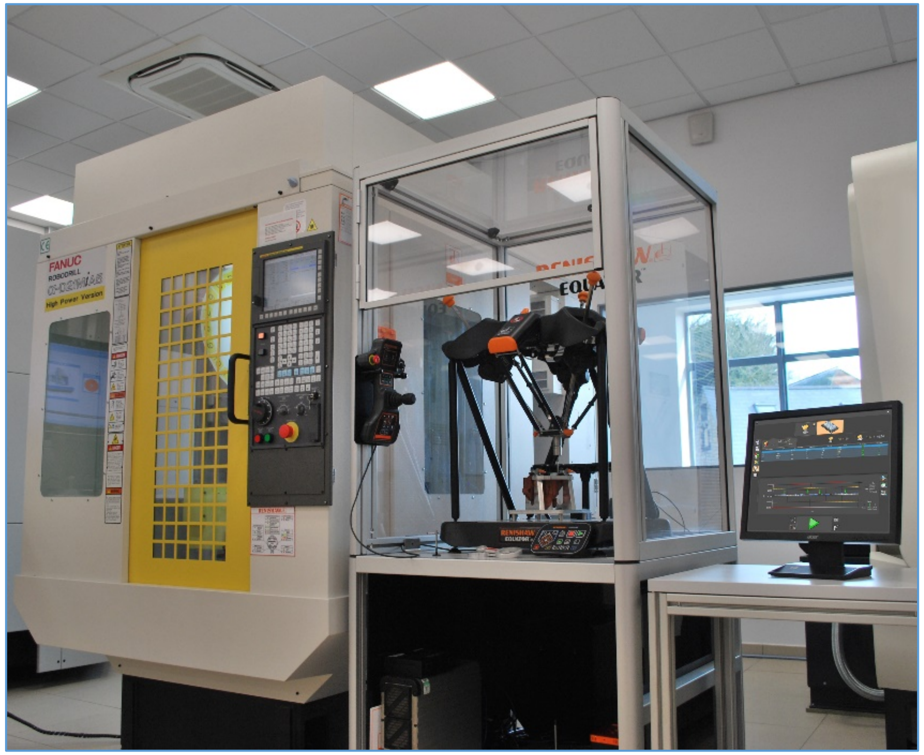
Process monitoring

Data handling

Observers - Sensors and Instruments

The view from Industry

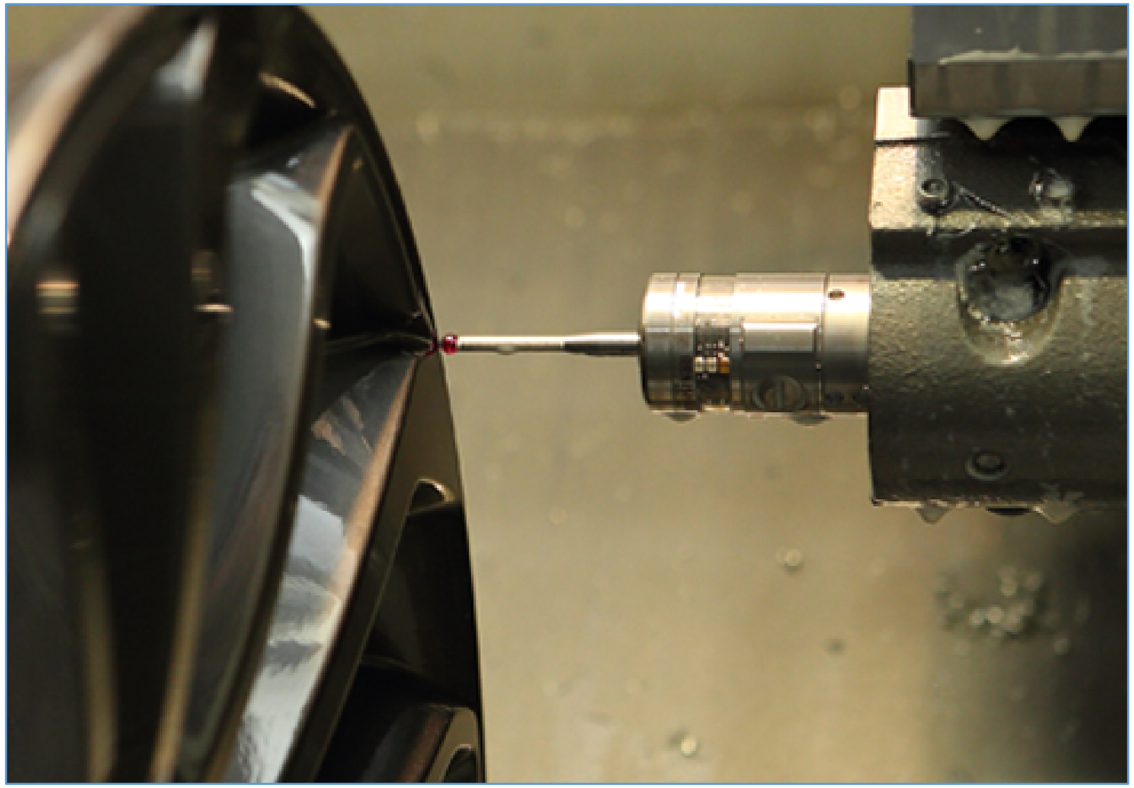
- **Closed-loop processes** require immediacy so measurement needs to be on the shop floor
- Measurement systems increasingly integrated into the process
- Integration is driving single platform, **multi-sensor** systems
- Measurement no longer simply for ‘tailgate’ inspection – data used for real-time adjustments



Geoff McFarland, Metrology, Metrology, Metrology (Three priorities for future manufacturing), 2017, Presentation at the Launch of the Advanced Metrology Hub, University of Huddersfield

Emerging trends – business drivers

- Product life cycles across many industries have reduced sharply over past decade – 10 years to just 2 years not unusual (e.g. smartphones and cars)
- Dedicated transfer lines have disappeared; production increasingly geared to lower volumes and greater flexibility
    - historically a single process was locked down and variability taken out over time
    - processes now have short life so little history; constant feedback required
    - metrology more important than ever to gain data for Pattern Learning: closed loop processes demand more measurement data



Geoff McFarland, Metrology, Metrology, Metrology (Three priorities for future manufacturing), 2017, Presentation at the Launch of the Advanced Metrology Hub, University of Huddersfield

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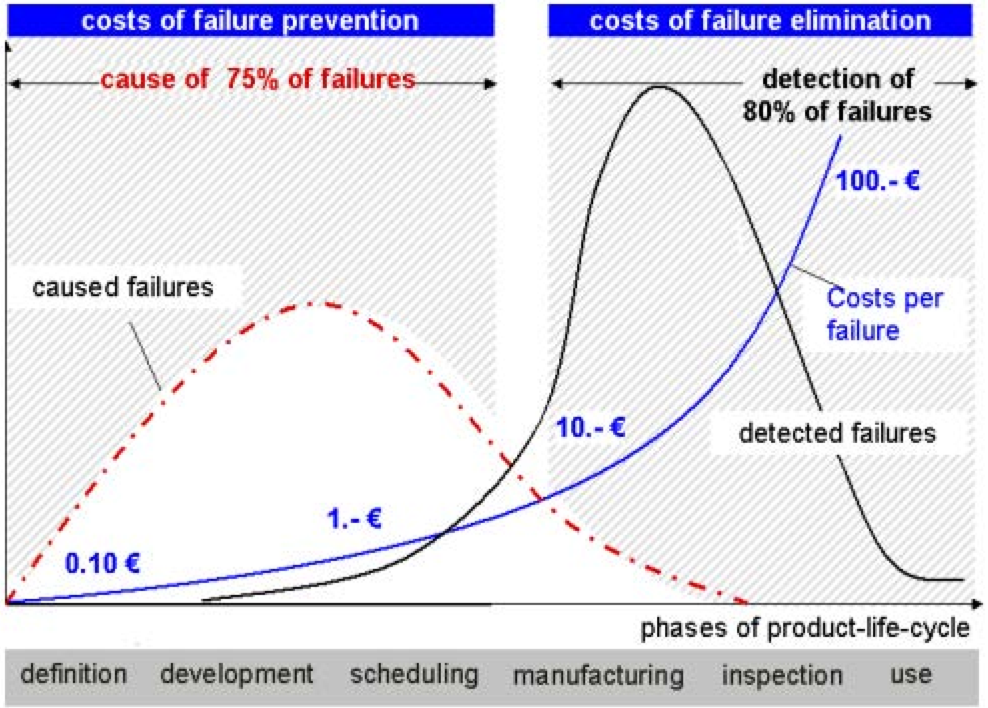
Why controlling/correcting early matters

- A common rule states, that
  - the costs for the elimination of errors increase by
  - about the factor of ten
  - for every further phase of the product life-cycle.
- In the phases of fixing of product properties and design of the components with the definition of their tolerances,
  - approximately 90% of the future costs of a product are originated by problems that are already implemented in the earlier phases.



H. Kunzmann, T. Pfeifer, R. Schmitt, H. Schwenke, A. Weckenmann, Productive Metrology - Adding Value to Manufacture, CIRP Annals, Volume 54, Issue 2, 2005, Pages 155-168

Process control - State of the Art review

The need for ***metrology*** in control

Layers of metrology-informed control

Measurement

- Traceability of measurement systems
- Uncertainty of measurement
  - Instrument
  - Method of application
  - Sampling rate and resolution
- The metrology approach gives confidence to the data

Control decision

- Deterministic, self-learning or hybrid algorithm
- Automatic or “informed manual” adjustment
- Effect on process stability
  - Traceability of adaption
- Metrology data informs the decision
- Metrology analogy can be applied to control algorithms

Control application

- Ability to adjust
  - Resolution
  - Responsiveness
- Timeliness of adjustment
- Ability to track changes
  - Effect on SPC
- Applying metrology to ensure hardware/ software capability

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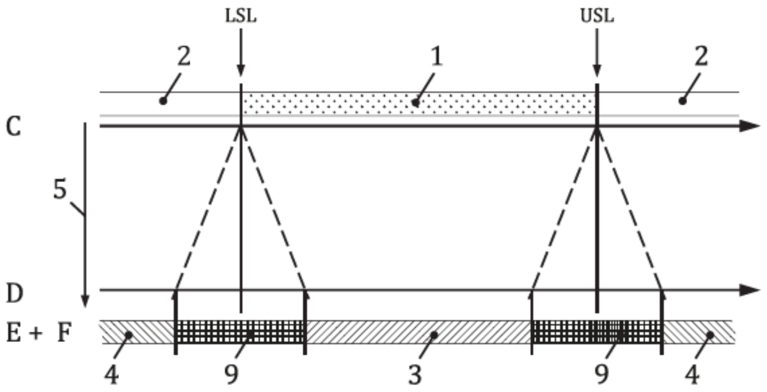
The Future Metrology Hub

Why metrology matters and complicates

- Design and manufacturing engineers need to understand how uncertainty of measurement affects conformity of finished products
- But do we think that control decisions based upon in-process measurements must be based upon this definition of conformance?
  - This could lead to **very** high cost of metrology



Key

C	design/specification phase
D	verification phase for a particular measurement uncertainty
E	verifying conformity (see 5.2)
F	verifying nonconformity (see 5.3)
1	specification zone
2	outside the specification zone
3	zone where conformity is verified
4	zone where nonconformity is verified
5	increasing measurement uncertainty reduces both the acceptance and rejection zones
9	uncertainty zone
LSL	lower specification limit
USL	upper specification limit

Figure 6 — Measurement uncertainty influences the zones where conformity or nonconformity can be verified

Geometrical product specifications (GPS) - Inspection by measurement of workpieces and measuring equipment - Part 1: Decision rules for verifying conformity or nonconformity with specifications (ISO 14253-1:2017)

Productive metrology

- To be productive, metrology information must generate knowledge that is **used as a basis for decisions and actions**.
- The term “Productive Metrology” was introduced to emphasise this claim.
- While cost of metrology in most cases can be easily evaluated, its benefit might not be immediately quantifiable at all times.

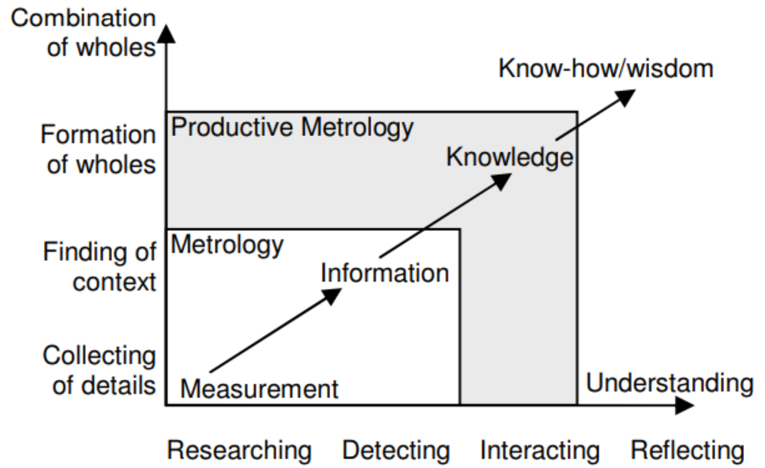


Figure 2: Gain of knowledge and development of wisdom / know-how as result of increasing experience and understanding.

Modified from: Nonaka, I., Takeuchi, H., 1995, The Knowledge Creating Company, New York/Oxford: Oxford University Press.

- Definition
  - The measurand shall be defined unambiguously
- Significance
  - The measurand shall reflect the functional requirements
- **Consequence**
  - **The result of a measurement shall be utilizable for making decisions**
- Adequacy
  - Measure with a measurement uncertainty adequate for the specification you want to control
- Vicinity
  - Measure as close as possible to the process you want to control
- **Reliability**
  - **Assure reliability of your metrology. It is the anchor of your product quality!**

H. Kunzmann, T. Pfeifer, R. Schmitt, H. Schwenke, A. Weckenmann, Productive Metrology - Adding Value to Manufacture, CIRP Annals, Volume 54, Issue 2, 2005, Pages 155-168

Control must be based upon "good" information (sensors)

- Analogy between the evolution of measuring instruments and of biological sensor systems
- The paper predicts the development of intelligent (smart) measuring instruments
    - self-correction,
    - provision of fault tolerance and of
    - forecast of the sensor ''metrological health".
- Will lead to the traceability of measurements under operation conditions with minimum costs.
- At the same time, the volume of routine calibrations will inevitably decrease.

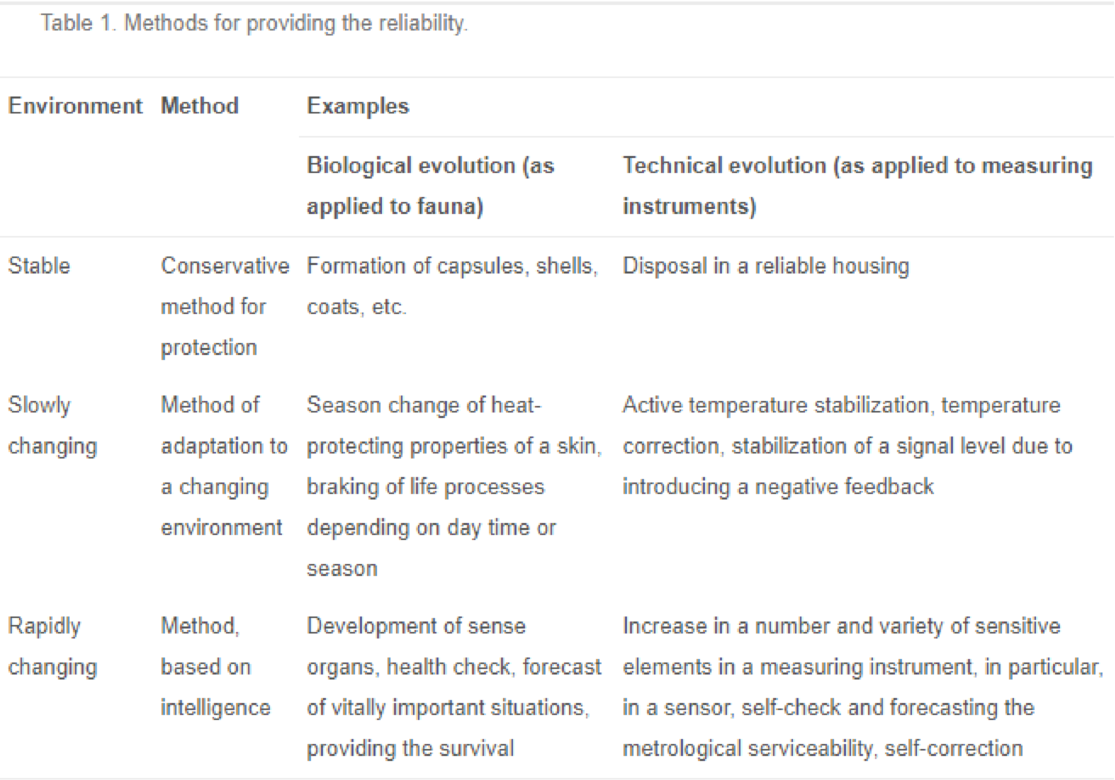


Table 1. Methods for providing the reliability.

Environment	Method	Examples	
		Biological evolution (as applied to fauna)	**Technical evolution (as applied to measuring instruments)**
Stable	Conservative method for protection	Formation of capsules, shells, coats, etc.	Disposal in a reliable housing
Slowly changing	Method of adaptation to a changing environment	Season change of heat-protecting properties of a skin, braking of life processes depending on day time or season	Active temperature stabilization, temperature correction, stabilization of a signal level due to introducing a negative feedback
Rapidly changing	Method, based on intelligence	Development of sense organs, health check, forecast of vitally important situations, providing the survival	Increase in a number and variety of sensitive elements in a measuring instrument, in particular, in a sensor, self-check and forecasting the metrological serviceability, self-correction

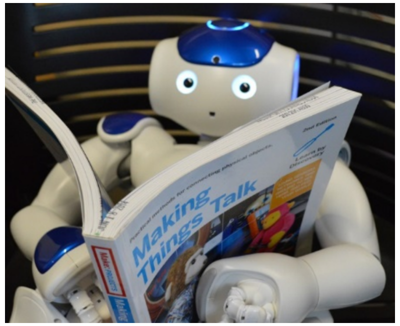
R. Taymanov, K. Sapozhnikova, Metrological self-check and evolution of metrology, Measurement 43 (2010) 869–877

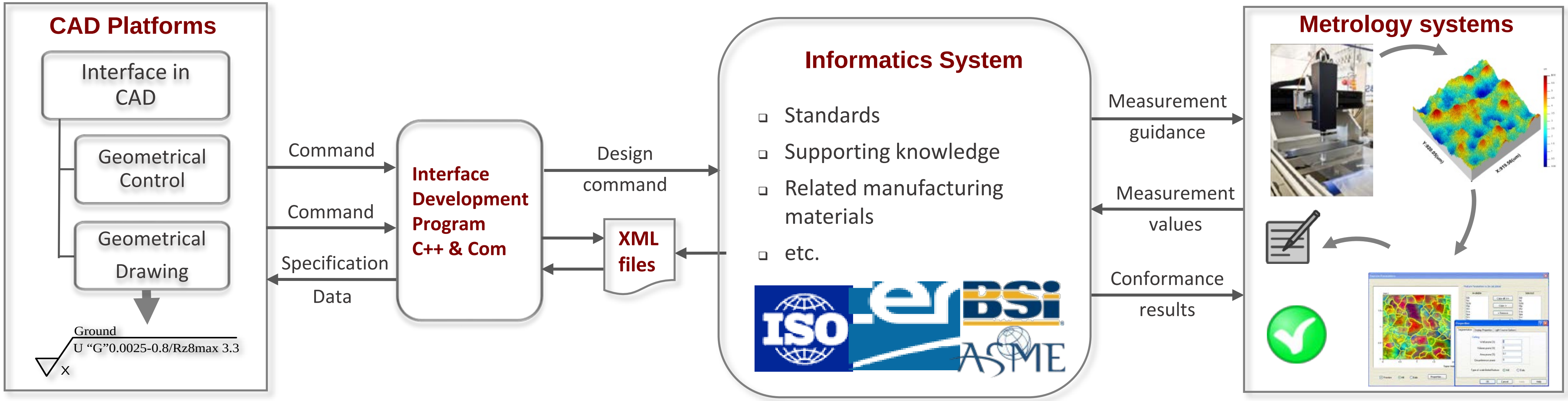
Data is a cost – knowledge is power

National/international standards, materials data-sheets, machining processing information, engineering experience, etc. is needed in machine readable format to permit control.

WIKIPEDIA
The Free Encyclopedia

ISI Web of KNOWLEDGE
Transforming Research





CAD Platforms

- Interface in CAD
  - Geometrical Control
  - Geometrical Drawing

Ground
U "G"0.0025-0.8/Rz8max 3.3
X

Command

Command

Specification Data

Interface Development Program C++ & Com

Design command

XML files

Informatics System

- Standards
- Supporting knowledge
- Related manufacturing materials
- etc.

ISO BSI ASME

Measurement guidance

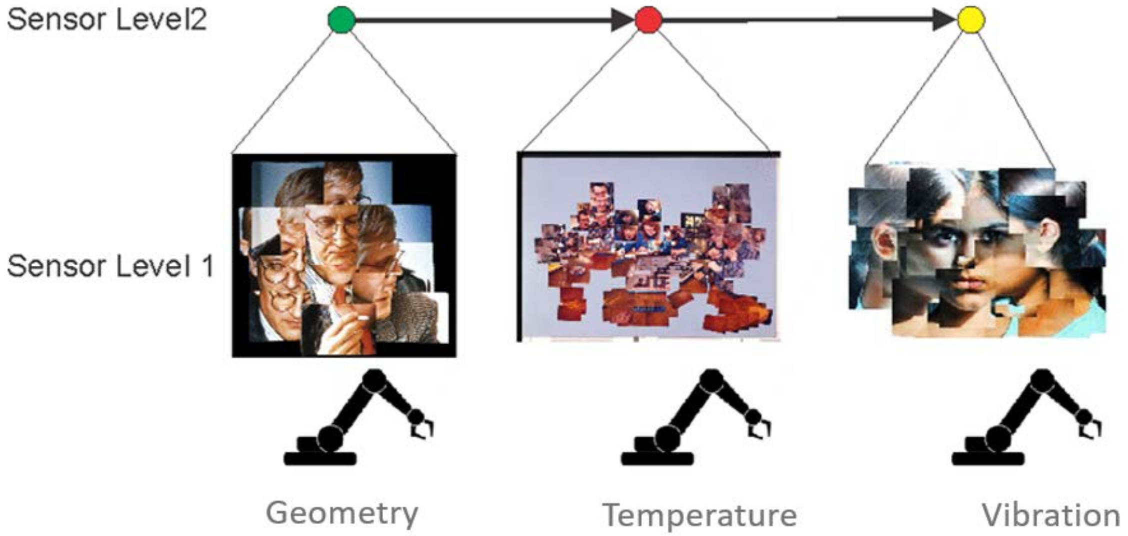
Measurement values

Conformance results

Metrology systems

Sensor Net/Data Analytics

- Metrology applied to
  - irregular structured networks (clusters, coarse graining hierarchies, sensor layers, etc.)
  - of disparate sensor types (geometrical, temperature, vibration, etc.)
  - to enable metrology operations and efficient optimised modelling
  - for advanced metrology for controlling the manufacturing process



Adapted from Paul Scott, Advanced Metrology Hub Launch event, University of Huddersfield, 2017. Artwork after David Hockney

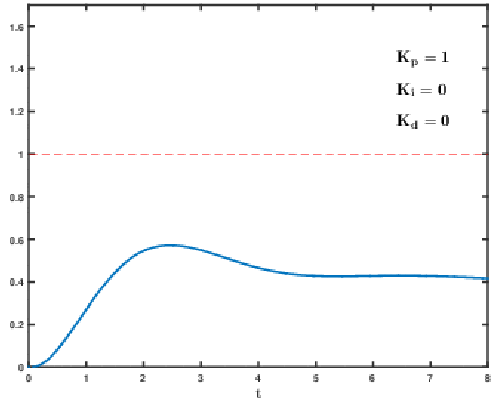
Process control - State of the Art review

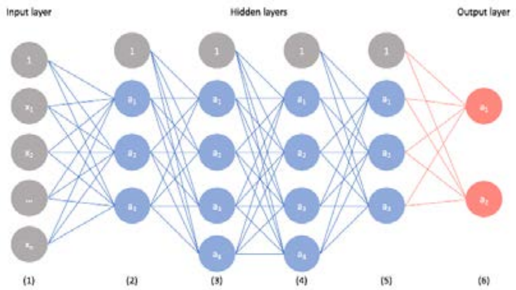
What is manufacturing control?

What is manufacturing control?

- Levels of control
  - Enterprise level planning and control of the when and where
  - Process control & optimization
  - Supply chain & supplier selection
  - Factory/cell level control
  - **Machine/ subsystem control**
  - **Part Program or assembly**
  - Scheduling and aggregate planning
  - Manufacturing systems flexibility
  - Quality control & monitoring
  - Maintenance systems
  - Demand forecasting
  - Manufacturing strategy & location decisions

- A control system
  - manages, commands, directs, or regulates the behaviour of other devices or systems using control loops.
- For continuously modulated control,
  - a feedback controller is used to automatically control a process or operation.
- For sequential and combinational logic,
  - software logic, such as in a programmable logic controller, is used.

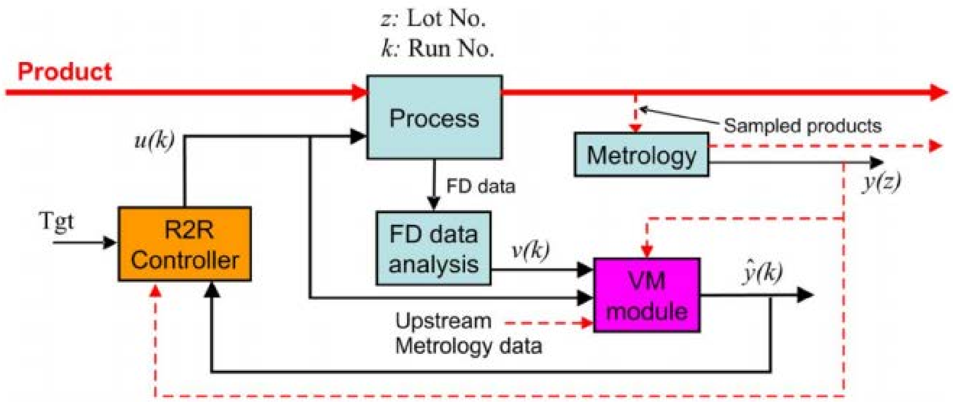


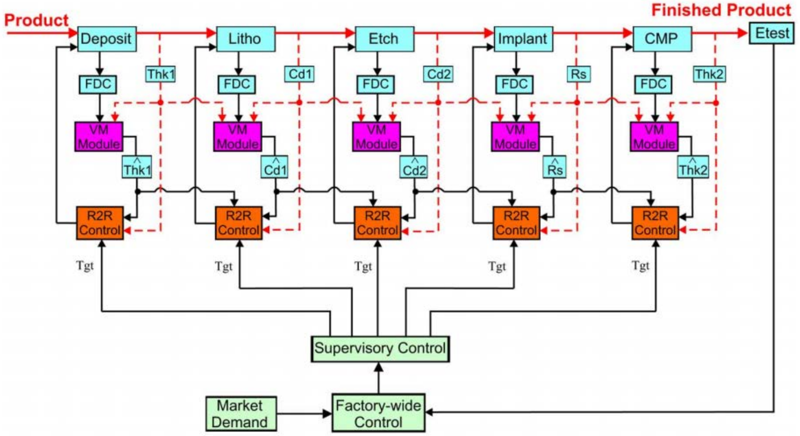


Classifications adapted from: A. Azadegan et al., Fuzzy logic in manufacturing: A review of literature and a specialized application, Int. J. Production Economics 132 (2011) 258–270. Images from: Wikipedia

Factory-wide control (semiconductor wafers)

- A factory-wide controller delivers control strategies to maximize an objective function consisting of factors such as
  - throughput, yield, cycle time, and fabrication cost.
- These control strategies along with market demands drive the electrical quality characteristics of the finished wafer.
- The desired electrical quality characteristics are then translated into individual target values for each processing step by a supervisory controller.

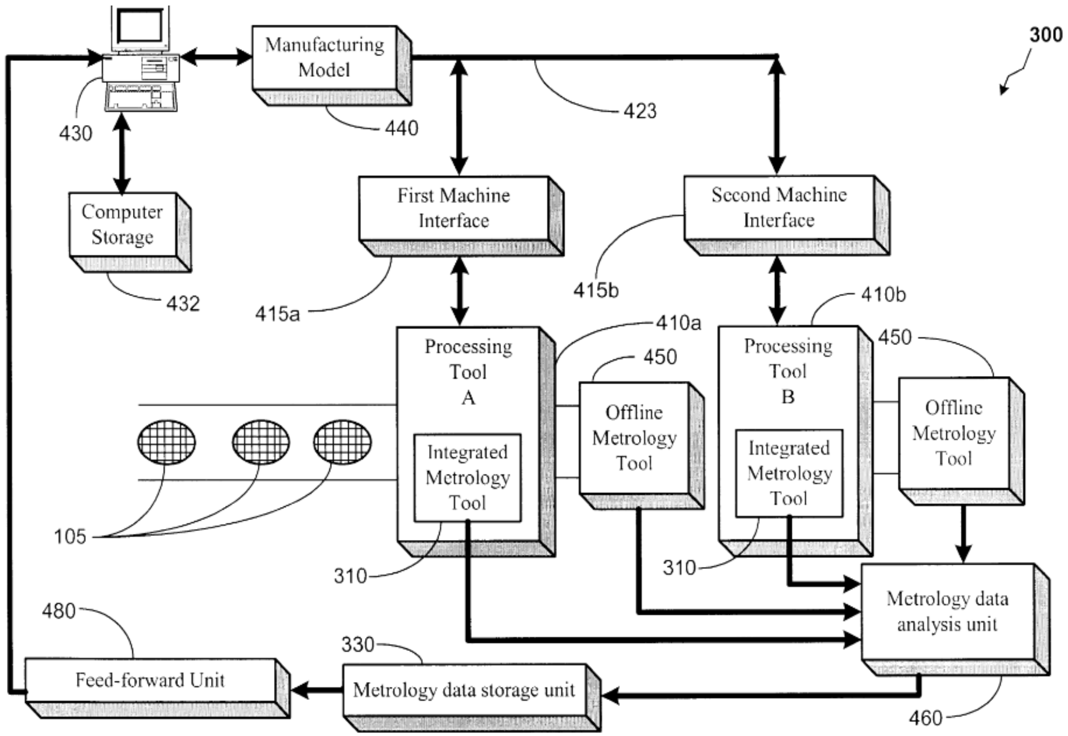




Aftab A. Khan, James R. Moyne, and Dawn M. Tilbury, 2007, An Approach for Factory-Wide Control Utilizing Virtual Metrology, IEEE Transactions on Semicondutor Manufacturing, Vol. 20, No. 4

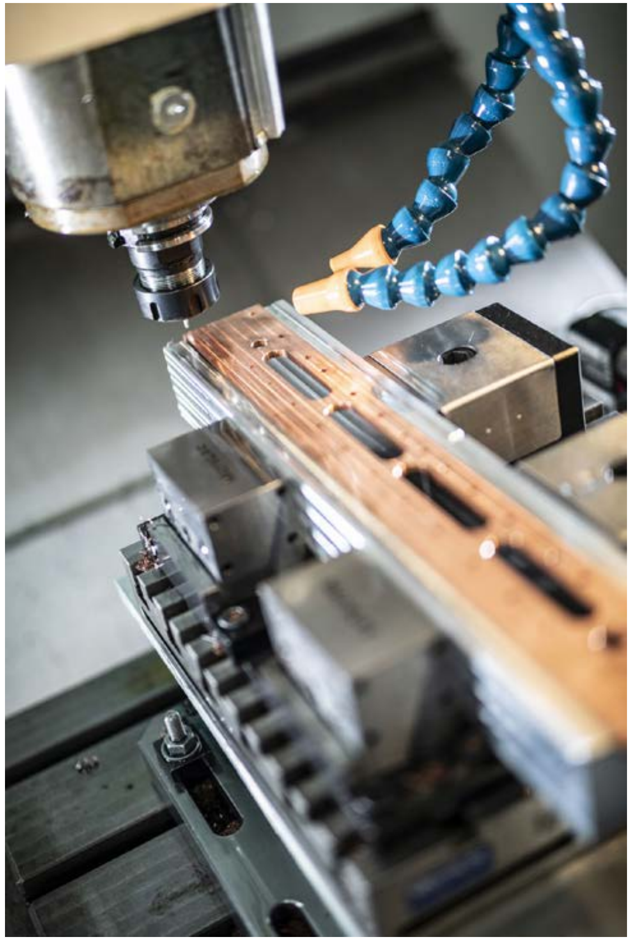
Patents exist for in-process metrology feeding into control

- A method and an apparatus for performing feed-forward correction during semiconductor wafer manufacturing.
- A first process on a semiconductor wafer is performed. Integrated metrology data related to the first process of the semiconductor wafer is acquired.
- An integrated metrology feed-forward process is performed based upon the integrated metrology data, the integrated metrology feed-forward process comprising identifying at least one error on the semiconductor wafer based upon the integrated metrology data related to the first process of the semiconductor wafer and performing an adjustment process to a second process to be performed on the wafer to compensate for the error.
- The second process on the semiconductor wafer is performed based upon the adjustment process.



US Patent US6708075B2 T. J. Sonderman, et. al. Method and apparatus for utilizing integrated metrology data as feed-forward data, 2001

Scope of this presentation is control of machine and assembly



- Machine
  - Structure/Geometry
  - Controller/CNC
  - Part program
- Assembly
  - Positioning
  - Orientation
  - Form/fit of locating features
- The control model only remains accurate for as long as the most recent measurement data truly represents the machine.

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Brutal/dirty assessment of research

EPSRC-funded research projects

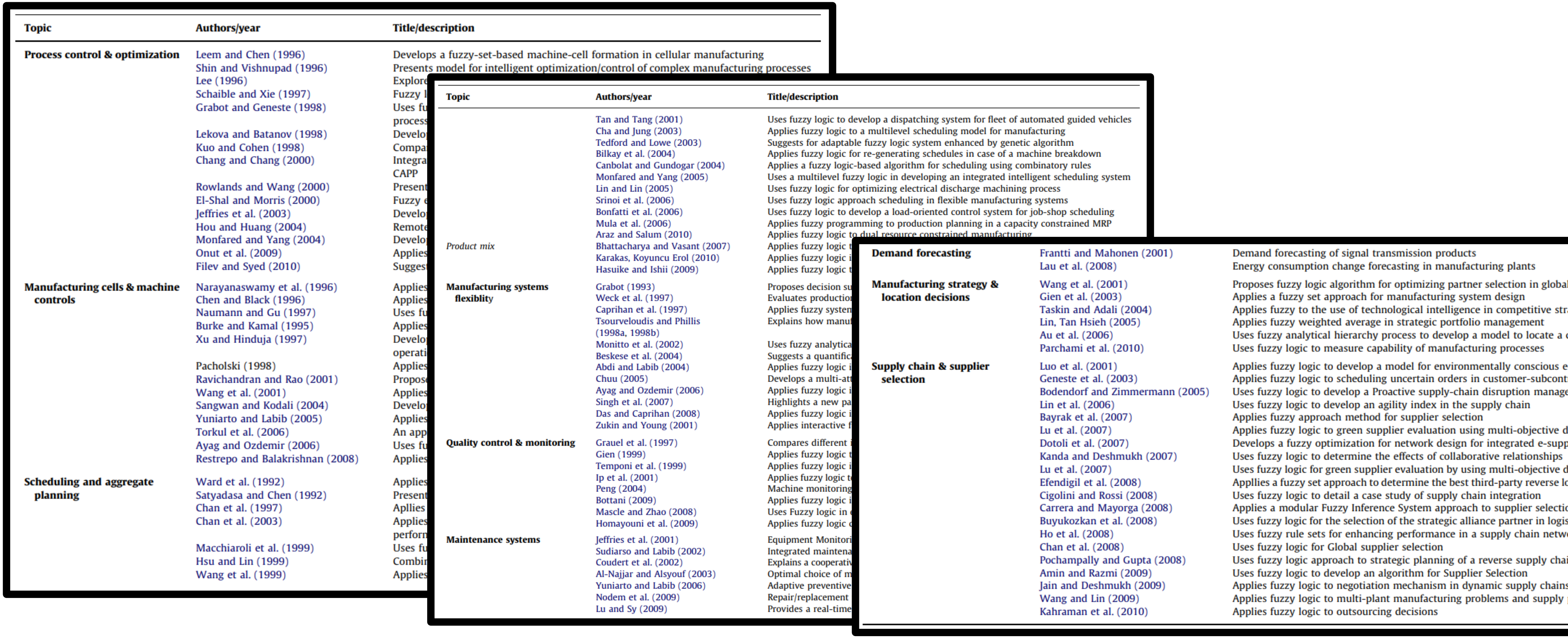
- Current projects matching "manufacturing AND control AND metrology"
  - 12 projects
  - £33.5M
  - Does include additive manufacturing and fluid dynamics ~£8M
- Source: EPSRC Visualise Our Portfolio: https://epsrc.ukri.org/research/ourportfolio/vop/

Journal publications (Scopus)

- 284 publications since 2015
  - Measurement Science and Technology
  - CIRP Annals Manufacturing Technology
  - Precision Engineering
  - International Journal of Advanced Manufacturing Technology
  - Measurement Journal of the International Measurement Confederation

Scopus search:
TITLE-ABS-KEY (manufacturing AND control AND metrology) AND (LIMIT-TO (DOCTYPE , "ar")) AND (EXCLUDE (EXACTKEYWORD , "Semiconductor Device Manufacture") OR EXCLUDE (EXACTKEYWORD , "Semiconductor Manufacturing") OR EXCLUDE (EXACTKEYWORD , "Silicon Wafers")) AND (LIMIT-TO (SRCTYPE , "j"))

Take just one control method – Fuzzy Logic



Topic	Authors/year	Title/description
Process control & optimization	Leem and Chen (1996)	Develops a fuzzy-set-based machine-cell formation in cellular manufacturing
	Shin and Vishnupad (1996)	Presents model for intelligent optimization/control of complex manufacturing processes
	Lee (1996)	Explore
	Schaible and Xie (1997)	Fuzzy l
	Grabot and Geneste (1998)	Uses fu process
	Lekova and Batanov (1998)	Develo
	Kuo and Cohen (1998)	Compa
	Chang and Chang (2000)	Integra CAPP
	Rowlands and Wang (2000)	Present
	El-Shal and Morris (2000)	Fuzzy
	Jeffries et al. (2003)	Develo
	Hou and Huang (2004)	Remote
	Monfared and Yang (2004)	Develo
	Onut et al. (2009)	Applies
	Filev and Syed (2010)	Suggest
Manufacturing cells & machine controls	Narayanaswamy et al. (1996)	Applies
	Chen and Black (1996)	Applies
	Naumann and Gu (1997)	Uses fu
	Burke and Kamal (1995)	Applies
	Xu and Hinduja (1997)	Develo operati
	Pacholski (1998)	Applies
	Ravichandran and Rao (2001)	Propos
	Wang et al. (2001)	Applies
	Sangwan and Kodali (2004)	Develo
	Yuniarto and Labib (2005)	Applies
	Torkul et al. (2006)	An app
	Ayag and Ozdemir (2006)	Uses fu
	Restrepo and Balakrishnan (2008)	Applies
Scheduling and aggregate planning	Ward et al. (1992)	Applies
	Satyadasa and Chen (1992)	Present
	Chan et al. (1997)	Apllies
	Chan et al. (2003)	Applies perforn
	Macchiaroli et al. (1999)	Uses fu
	Hsu and Lin (1999)	Combin
	Wang et al. (1999)	Applies

Topic	Authors/year	Title/description
	Tan and Tang (2001)	Uses fuzzy logic to develop a dispatching system for fleet of automated guided vehicles
	Cha and Jung (2003)	Applies fuzzy logic to a multilevel scheduling model for manufacturing
	Tedford and Lowe (2003)	Suggests for adaptable fuzzy logic system enhanced by genetic algorithm
	Bilkay et al. (2004)	Applies fuzzy logic for re-generating schedules in case of a machine breakdown
	Canbolat and Gundogar (2004)	Applies a fuzzy logic-based algorithm for scheduling using combinatory rules
	Monfared and Yang (2005)	Uses a multilevel fuzzy logic in developing an integrated intelligent scheduling system
	Lin and Lin (2005)	Uses fuzzy logic for optimizing electrical discharge machining process
	Srinoi et al. (2006)	Uses fuzzy logic approach scheduling in flexible manufacturing systems
	Bonfatti et al. (2006)	Uses fuzzy logic to develop a load-oriented control system for job-shop scheduling
	Mula et al. (2006)	Applies fuzzy programming to production planning in a capacity constrained MRP
	Araz and Salum (2010)	Applies fuzzy logic to dual resource constrained manufacturing
Product mix	Bhattacharya and Vasant (2007)	Applies fuzzy logic t
	Karakas, Koyuncu Erol (2010)	Applies fuzzy logic i
	Hasuike and Ishii (2009)	Applies fuzzy logic t
Manufacturing systems flexiblity	Grabot (1993)	Proposes decision su
	Weck et al. (1997)	Evaluates productio
	Caprihan et al. (1997)	Applies fuzzy system
	Tsourveloudis and Phillis (1998a, 1998b)	Explains how manu
	Monitto et al. (2002)	Uses fuzzy analytica
	Beskese et al. (2004)	Suggests a quantifica
	Abdi and Labib (2004)	Applies fuzzy logic i
	Chuu (2005)	Develops a multi-att
	Ayag and Ozdemir (2006)	Applies fuzzy logic i
	Singh et al. (2007)	Highlights a new pa
	Das and Caprihan (2008)	Applies fuzzy logic i
	Zukin and Young (2001)	Applies interactive f
Quality control & monitoring	Grauel et al. (1997)	Compares different i
	Gien (1999)	Applies fuzzy logic t
	Temponi et al. (1999)	Applies fuzzy logic i
	Ip et al. (2001)	Applies fuzzy logic t
	Peng (2004)	Machine monitoring
	Bottani (2009)	Applies fuzzy logic i
	Mascle and Zhao (2008)	Uses Fuzzy logic in
	Homayouni et al. (2009)	Applies fuzzy logic c
Maintenance systems	Jeffries et al. (2001)	Equipment Monitori
	Sudiarso and Labib (2002)	Integrated maintena
	Coudert et al. (2002)	Explains a cooperativ
	Al-Najjar and Alsyouf (2003)	Optimal choice of m
	Yuniarto and Labib (2006)	Adaptive preventive
	Nodem et al. (2009)	Repair/replacement
	Lu and Sy (2009)	Provides a real-time

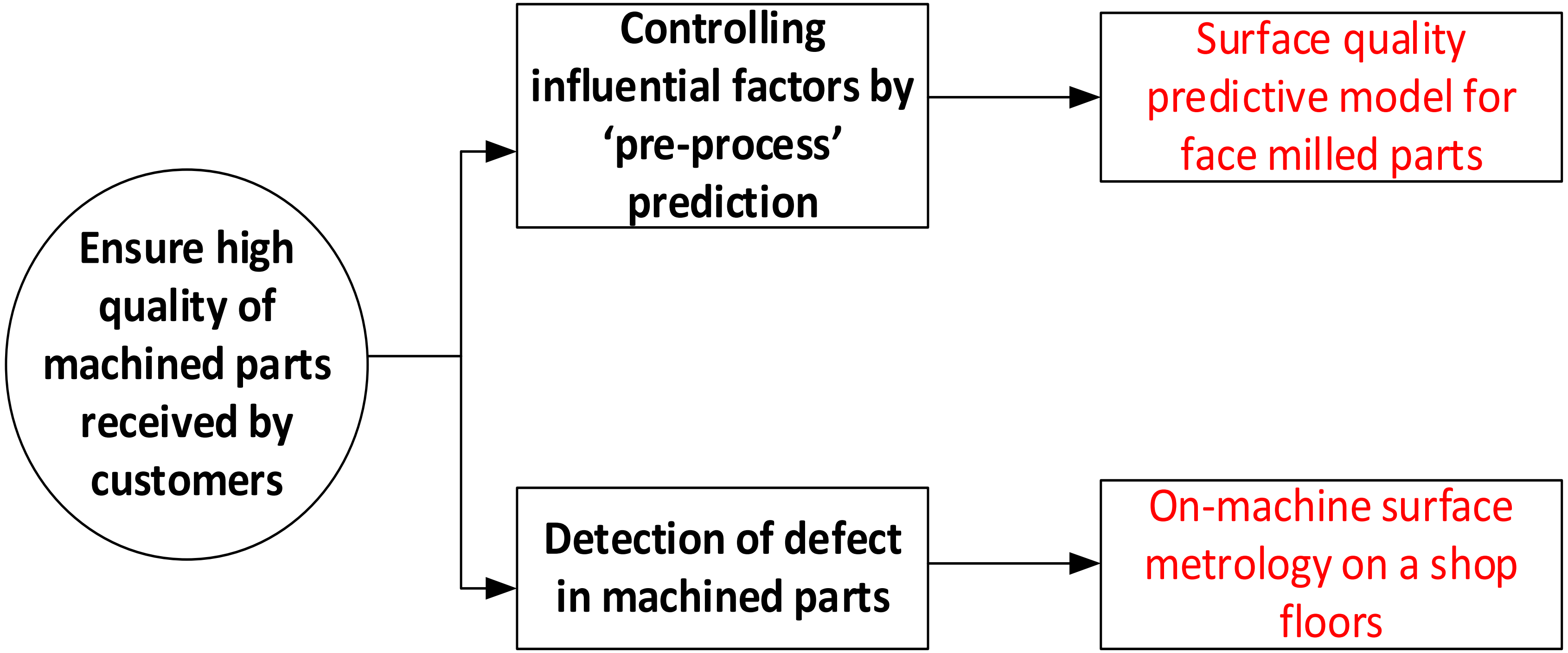
Demand forecasting	Frantti and Mahonen (2001)	Demand forecasting of signal transmission products
	Lau et al. (2008)	Energy consumption change forecasting in manufacturing plants
Manufacturing strategy & location decisions	Wang et al. (2001)	Proposes fuzzy logic algorithm for optimizing partner selection in global
	Gien et al. (2003)	Applies a fuzzy set approach for manufacturing system design
	Taskin and Adali (2004)	Applies fuzzy to the use of technological intelligence in competitive str
	Lin, Tan Hsieh (2005)	Applies fuzzy weighted average in strategic portfolio management
	Au et al. (2006)	Uses fuzzy analytical hierarchy process to develop a model to locate a
	Parchami et al. (2010)	Uses fuzzy logic to measure capability of manufacturing processes
Supply chain & supplier selection	Luo et al. (2001)	Applies fuzzy logic to develop a model for environmentally conscious e
	Geneste et al. (2003)	Applies fuzzy logic to scheduling uncertain orders in customer-subcont
	Bodendorf and Zimmermann (2005)	Uses fuzzy logic to develop a Proactive supply-chain disruption manage
	Lin et al. (2006)	Uses fuzzy logic to develop an agility index in the supply chain
	Bayrak et al. (2007)	Applies fuzzy approach method for supplier selection
	Lu et al. (2007)	Applies fuzzy logic to green supplier evaluation using multi-objective d
	Dotoli et al. (2007)	Develops a fuzzy optimization for network design for integrated e-supp
	Kanda and Deshmukh (2007)	Uses fuzzy logic to determine the effects of collaborative relationships
	Lu et al. (2007)	Uses fuzzy logic for green supplier evaluation by using multi-objective d
	Efendigil et al. (2008)	Appllies a fuzzy set approach to determine the best third-party reverse lo
	Cigolini and Rossi (2008)	Uses fuzzy logic to detail a case study of supply chain integration
	Carrera and Mayorga (2008)	Applies a modular Fuzzy Inference System approach to supplier selectio
	Buyukozkan et al. (2008)	Uses fuzzy logic for the selection of the strategic alliance partner in logis
	Ho et al. (2008)	Uses fuzzy rule sets for enhancing performance in a supply chain netw
	Chan et al. (2008)	Uses fuzzy logic for Global supplier selection
	Pochampally and Gupta (2008)	Uses fuzzy logic approach to strategic planning of a reverse supply chai
	Amin and Razmi (2009)	Uses fuzzy logic to develop an algorithm for Supplier Selection
	Jain and Deshmukh (2009)	Applies fuzzy logic to negotiation mechanism in dynamic supply chains
	Wang and Lin (2009)	Applies fuzzy logic to multi-plant manufacturing problems and supply
	Kahraman et al. (2010)	Applies fuzzy logic to outsourcing decisions

A. Azadegan et al., Fuzzy logic in manufacturing: A review of literature and a specialized application, Int. J. Production Economics 132 (2011) 258–270

Process control - State of the Art review

Predictive versus adaptive control

Approaches to control



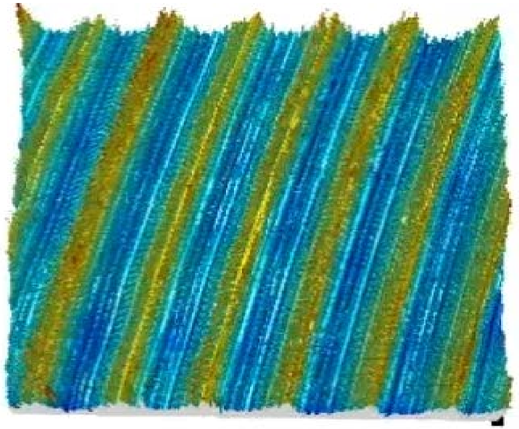
Ensure high quality of machined parts received by customers

Controlling influential factors by 'pre-process' prediction

Surface quality predictive model for face milled parts

Detection of defect in machined parts

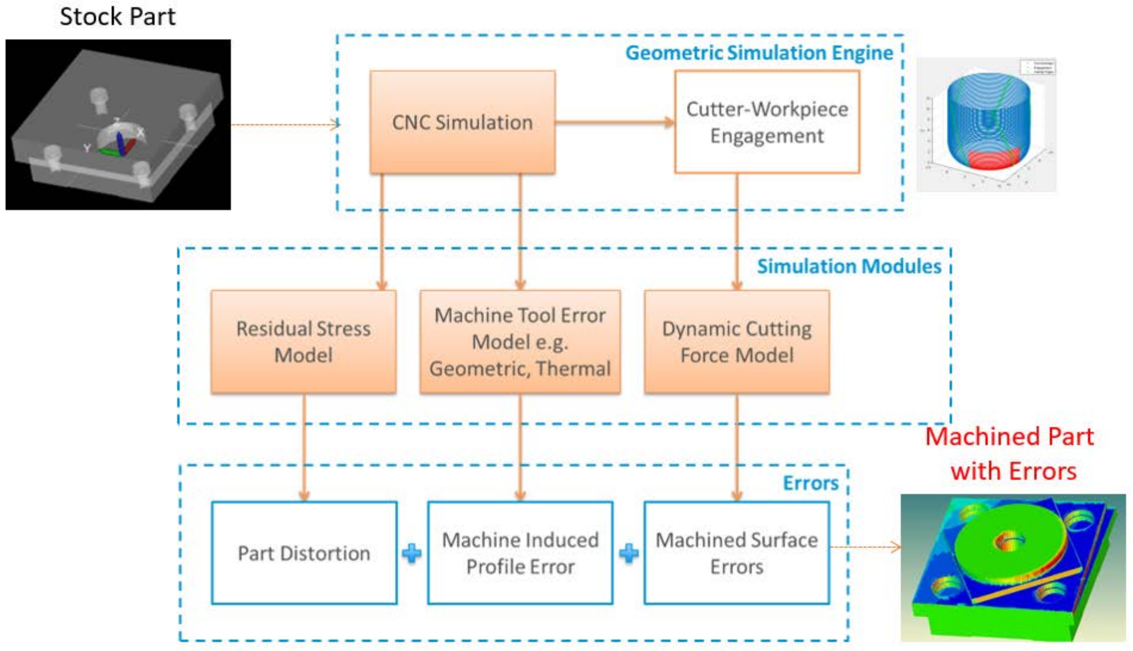
On-machine surface metrology on a shop floors



Akowua, Kwame D.B, Fletcher, Simon, Longstaff, Andrew P. and Mian, Naeem S. (2017) *Areal surface measurement using multidirectional laser line scanning.* In: Laser Metrology and Machine Performance XII, Lamdamap 2017. euspen

Predictive modelling

- Creating a single “virtual machine” (digital twin) model of the machine and process
- Using metrology data to calibrate the model
  - Pre-calibrated data from the machine between processes
  - Allows off-line decisions
- Future developments will allow it to be updated with sensor data
  - Allows on-line control



Stock Part

Geometric Simulation Engine

CNC Simulation

Cutter-Workpiece Engagement

Simulation Modules

Residual Stress Model

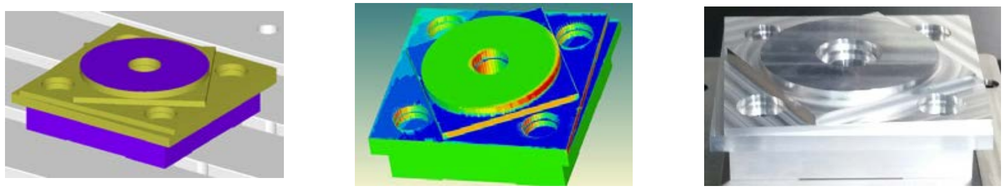
Machine Tool Error Model e.g. Geometric, Thermal

Dynamic Cutting Force Model

Errors

Part Distortion + Machine Induced Profile Error + Machined Surface Errors

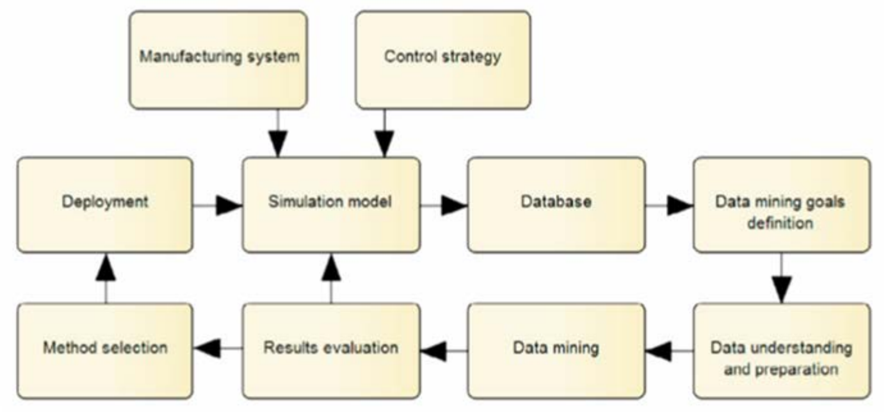
Machined Part with Errors

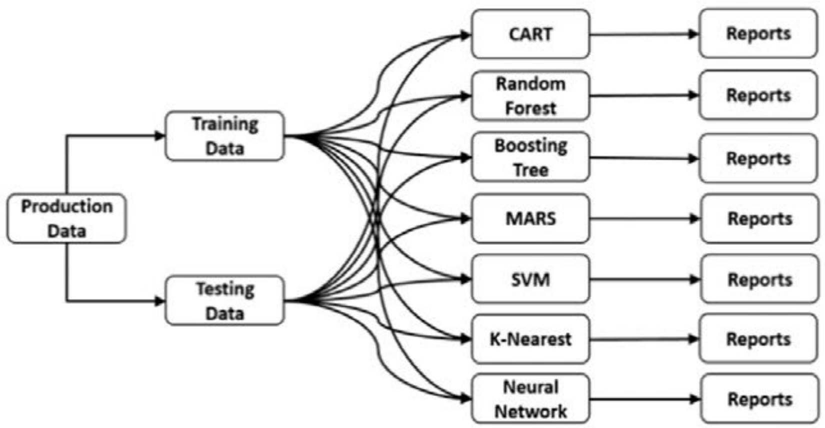


Ozkirimli,O., Fletcher, S., Kite,J., Longstaff, A.P., McVey,S., Ozturk, E., (2017), Modelling and visualisation of machine tool and process related form errors, 6th International Conference on Virtual Machining Process Technology (VMPT), Montréal, May 29th – June 2nd, 2017

Data mining methods

- The Industry 4.0 concept assumes that modern manufacturing systems generate huge amounts of data that must be collected, stored, managed and analysed
- The case study is focused on predicting the manufacturing process behaviour according to production data
- The paper presents the way of gaining knowledge about the future behaviour of manufacturing system by data mining predictive tasks.
- The predictions of the manufacturing process behaviour were implemented by varying the input parameters using selected methods and techniques of data mining. The predicted process behaviour was verified using the simulation model.
- The authors analysed different methods. The neural network method was selected for deploying new data by PMML files in the final phases.

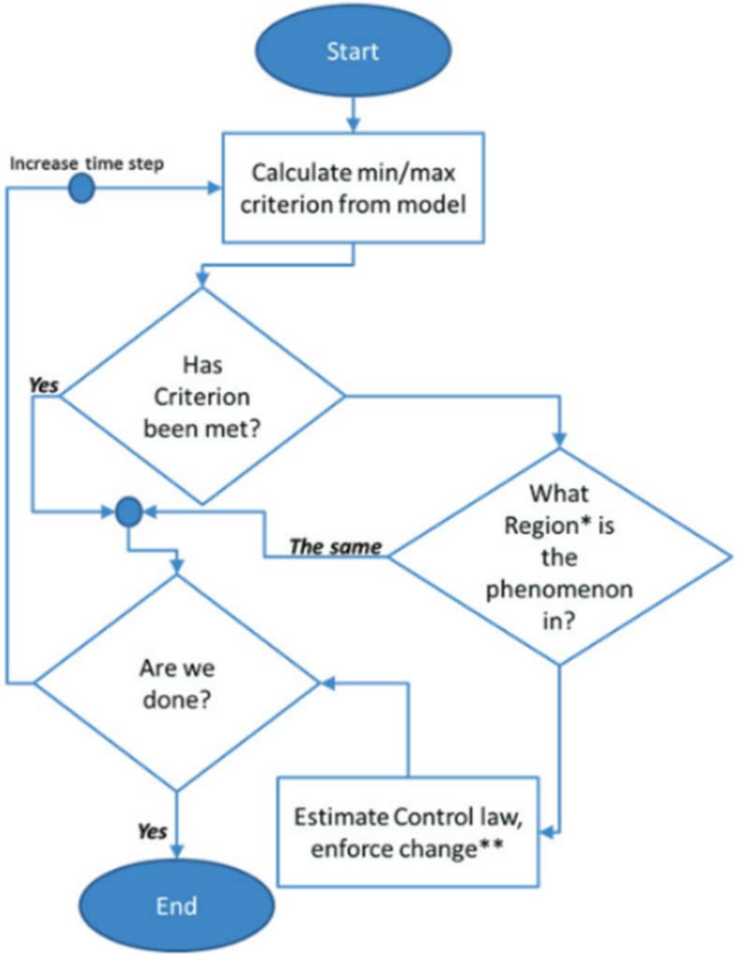




P. Vazan, D. Janikova, P. Tanuska, M.Kebisek, Z. Cervenanska, Using data mining methods for manufacturing process control, IFAC-PapersOnLine, Volume 50, Issue 1, July 2017, Pages 6178-6183

Hybrid models

- Two examples of Laser-based Manufacturing are deployed in order to verify the response of adaptive control algorithms through empirical design
  - Laser welding and Laser-based Additive Manufacturing processes.
- The penetration depth has been utilized as the quality criterion of the adaptive control loop for both processes.
  - The solidification phase has also been examined.
- Fast estimation of the control law has to be made.
  - FPGAs are proposed as the solution.
- Quality assessment algorithms, fusing real time data with (hierarchical) physical models, should be elaborated in order for holistic process control to be achieved.



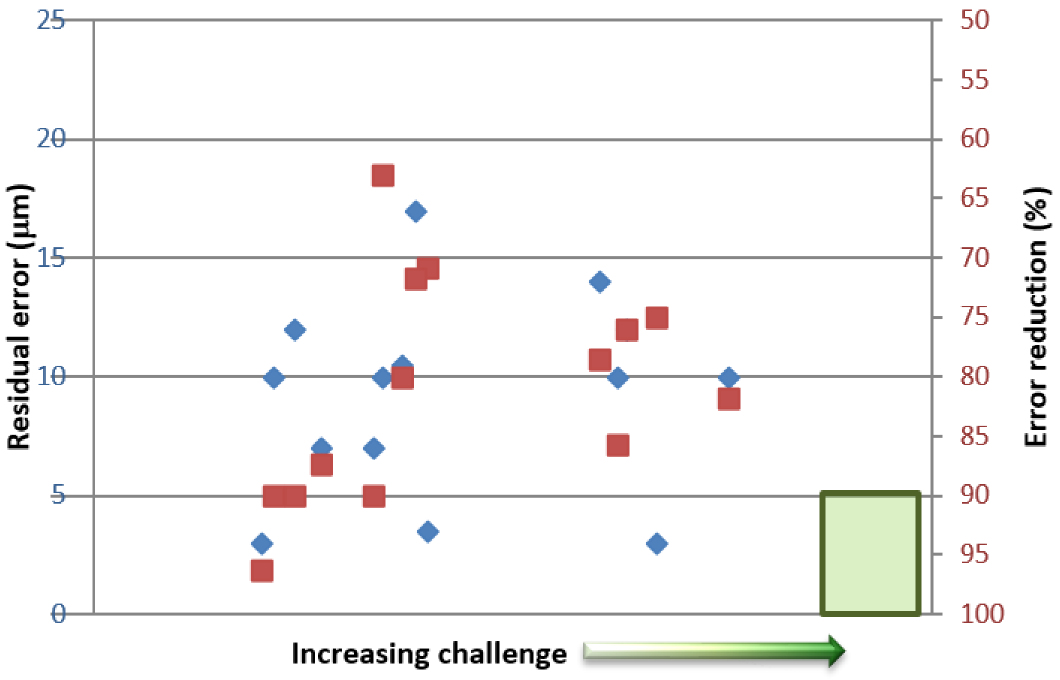
Alexios Papacharalampopoulos, Panagiotis Stavropoulos, John Stavridis, Adaptive control of thermal processes: laser welding and additive manufacturing paradigms, Procedia CIRP, Volume 67, 2018, Pages 233-237

Process control - State of the Art review

Case study – thermal distortion in machine tools

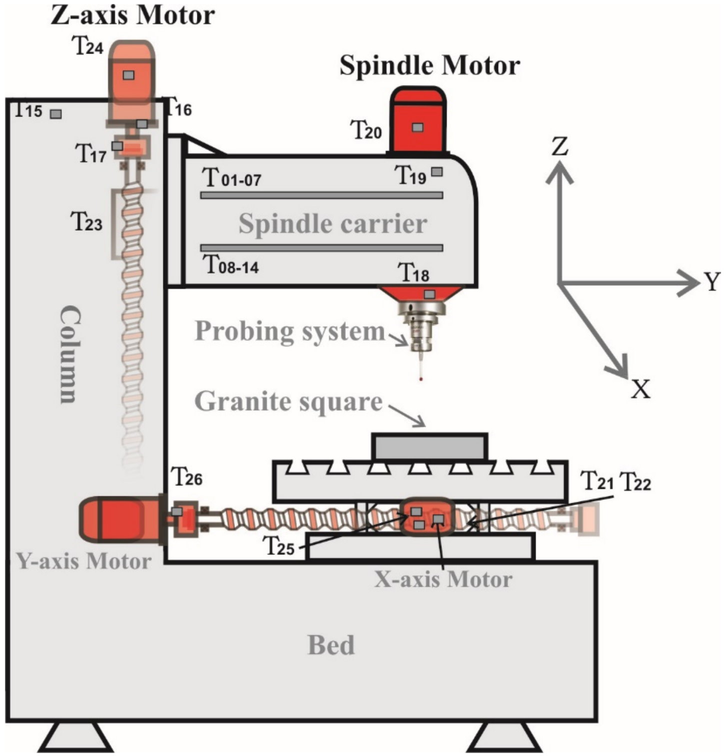
Results of critique of machine tool thermal compensation literature

- Maximum challenge:
  - Compensation in all axis directions
  - Validation from long term part production
  - Position dependent thermal error on all axes
- Minimum challenge
  - Single direction
  - Single heat source
  - Position independent only
  - Short validation similar to model training data

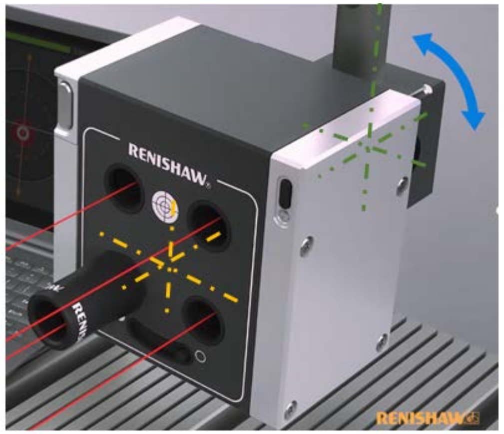


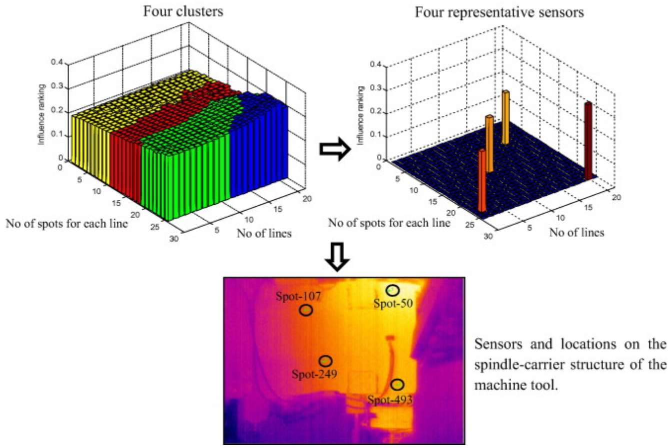
Critique was of 18 of the most relevant/prestigious journal papers published circa 2010

Metrology – what is needed for model training?



- Training models with metrology-level equipment
  - Renishaw XM-60
  - Lion Precision Spindle Error Analyser
  - Probing of stable, calibrated artefacts
- Application of the right sensors in the right place
- Rigorous DoE during training





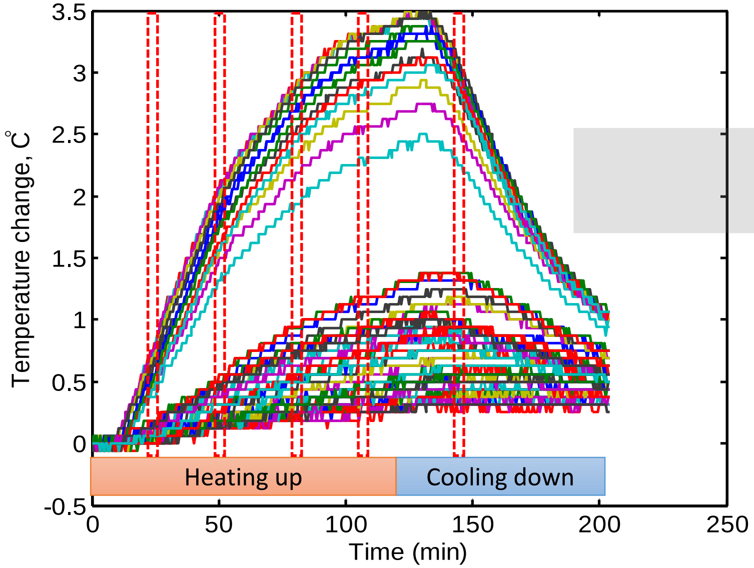
Sensors and locations on the spindle-carrier structure of the machine tool.

AM Abdulshahed, AP Longstaff, S Fletcher, A Myers, Thermal error modelling of machine tools based on ANFIS with fuzzy c-means clustering using a thermal imaging camera, Applied Mathematical Modelling 39 (7), 1837-1852

AM Abdulshahed, AP Longstaff, S Fletcher, The Application of ANN and ANFIS Prediction Models for Thermal Error Compensation on CNC Machine Tools, Applied Soft Computing 27, 158-168

ANFIS model - temperature and strain

Model inputs



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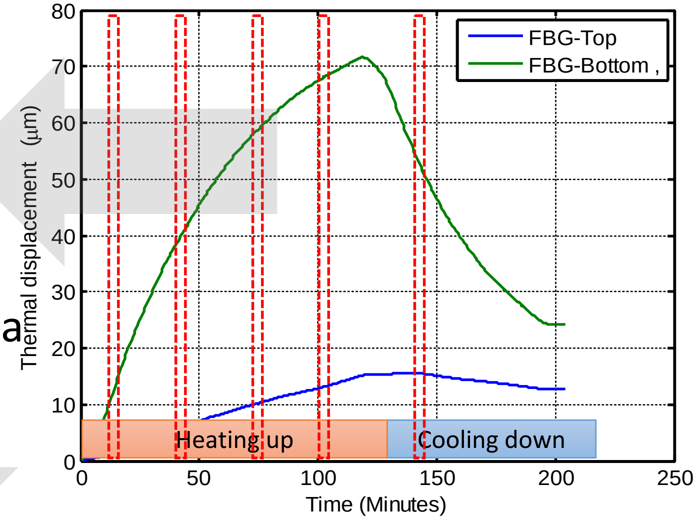
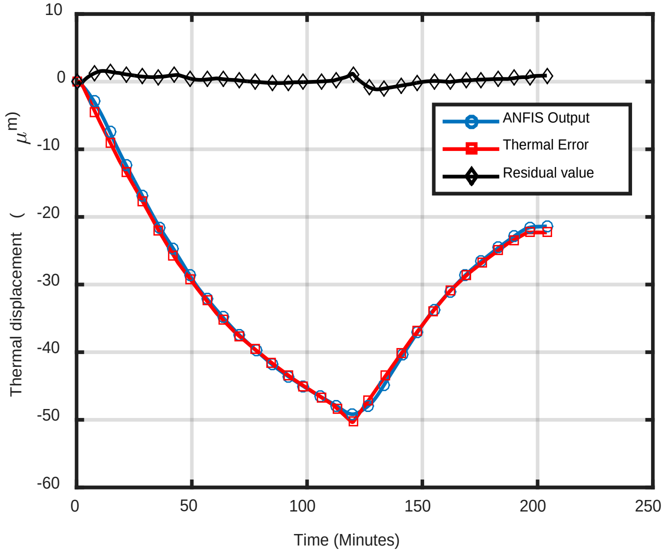
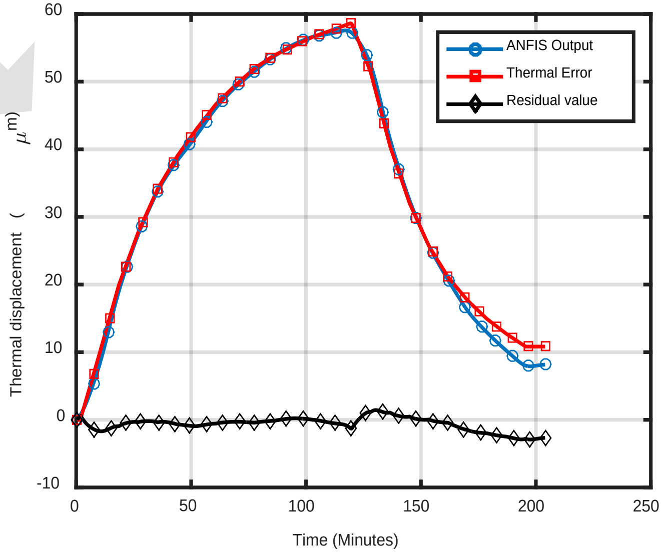


Fusion data

ANFIS

Model output- Y direction

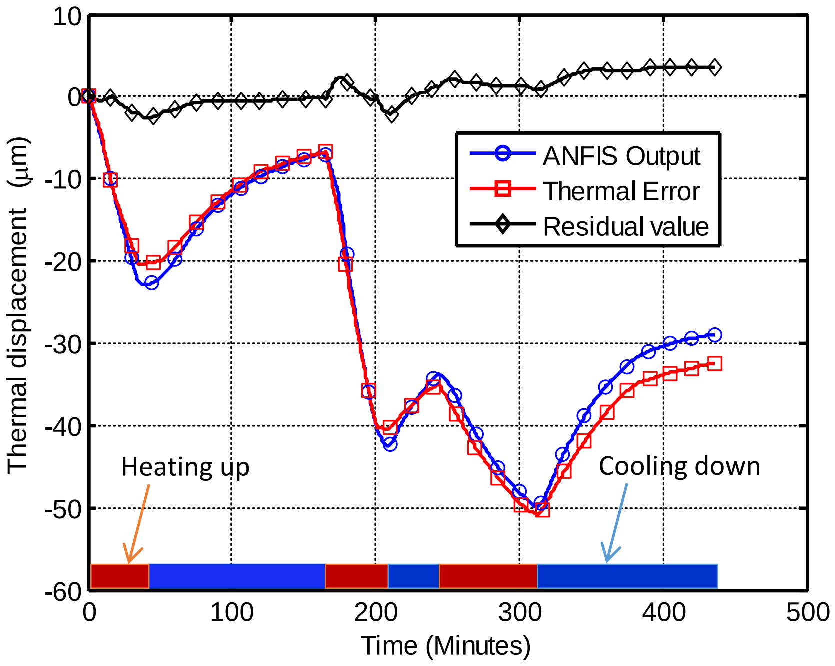




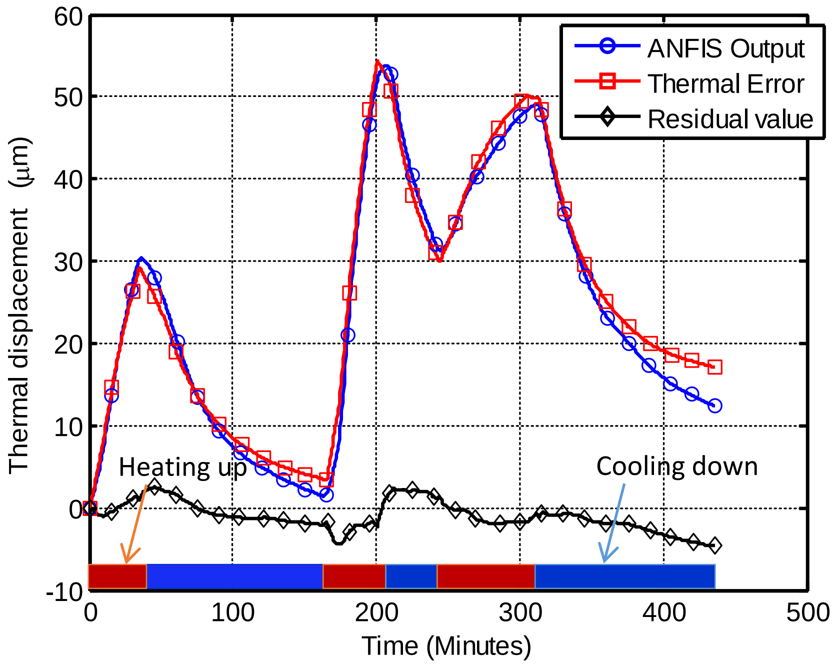
Model output- Z direction

Model validation- unseen dataset

Model output- Y direction



Model output- Z direction

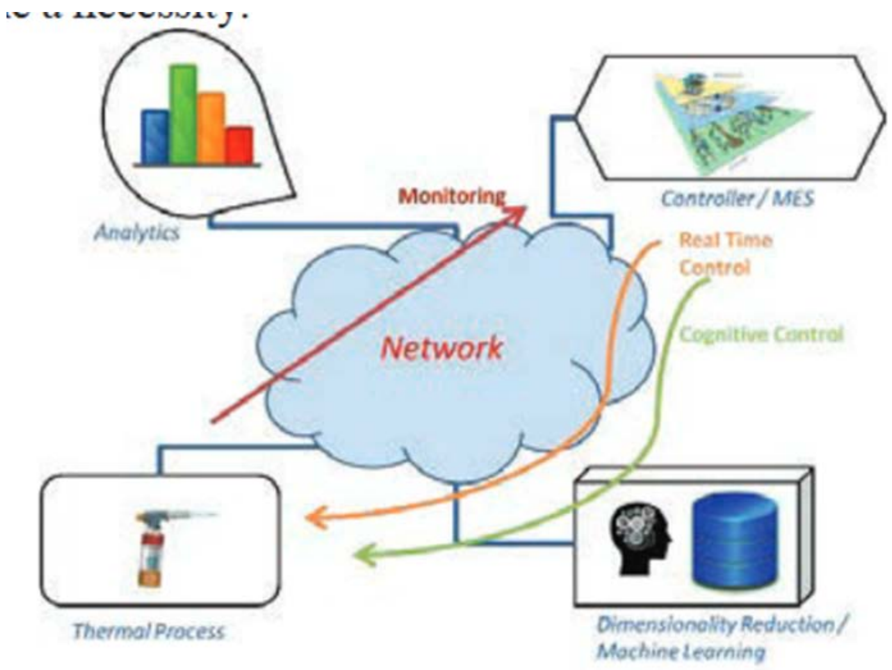


Process control - State of the Art review

Cloud-based control

Cloud-based control of thermal processes

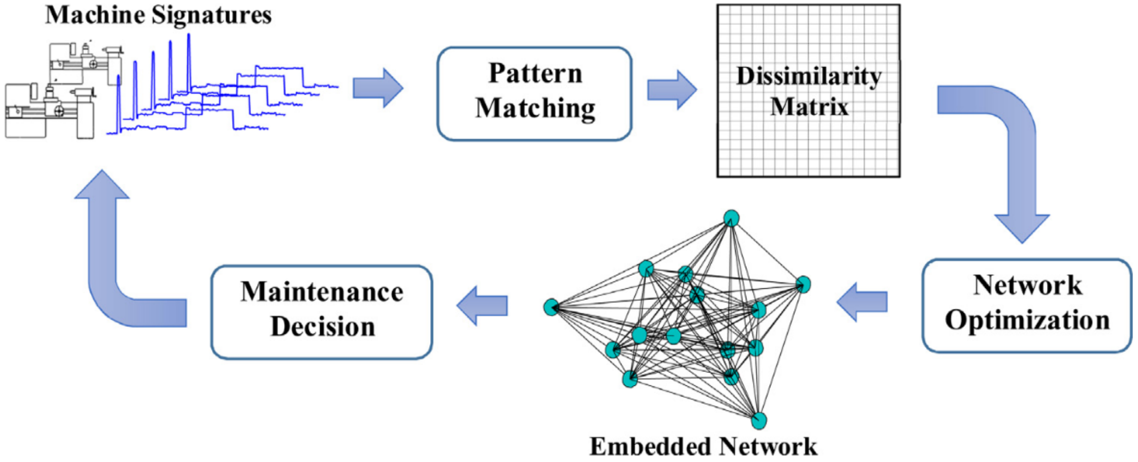
- Process control require handling of big data.
- Intelligent algorithms that reduce the dimensionality of the data will have sufficient weighting in the future to avoid storage and processing costs
- Simple static controllers are useful in manufacturing systems
  - simple structure
  - speed
  - Relatively transparent and low-cost implementation
- In the future, networked control will have to be taken into account, especially in the case of centralized control through non-dedicated networks.
  - Latency in data transfer
- Simple gain controllers achieved good results in terms of dealing with time delays in signals



Alexios Papacharalampopoulos, John Stavridis, Panagiotis Stavropoulos, George Chryssolouris, Cloud-based Control of Thermal Based Manufacturing Processes, Procedia CIRP, Volume 55, 2016, Pages 254-259

Control of tool wear and chatter

- An effective sensor network to monitor online tool wear status and chattering
  - Task 1: Systems feature recognition
  - Task 2: Network construction based on Node-to-Node Distance
  - Task 3: Parallel computing method for optimizing network performance
- Tasks decentralized:
  - Applying dynamic warping algorithm for system dissimilarity
  - Developed Stochastic network embedding algorithm with parallel computing technology
  - Dimensionality reduction: the new network effectively concluded the system condition information through high dimensional data
  - Visual analytics: the network provides a good traceable function that allows users to monitor its workflows
  - High Performance Computing (HPC) is applied to boost the performance of network efficiency



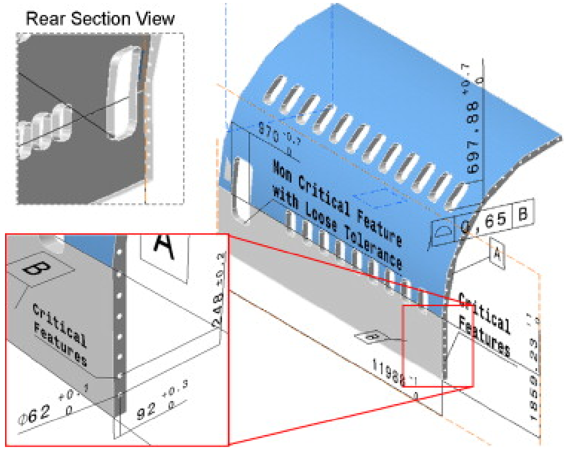
Chen Kana, Hui Yang, Soundar Kumara, Parallel computing and network analytics for fast Industrial Internet-of-Things (IIoT) machine information processing and condition monitoring, Journal of Manufacturing Systems 46 (2018) 282–293

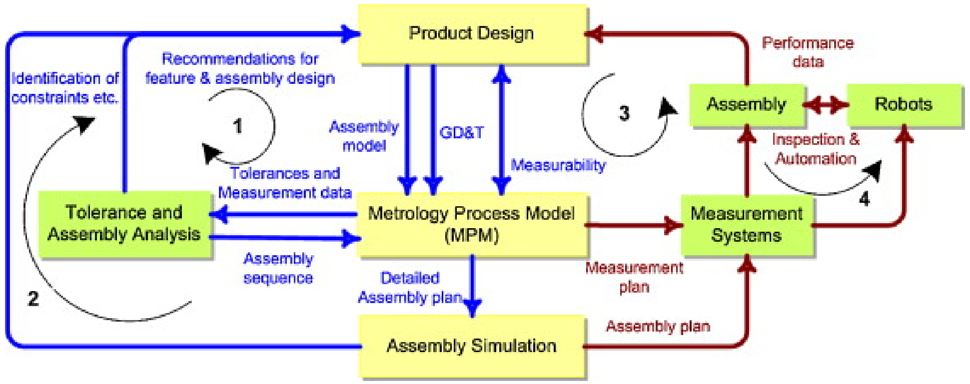
Process control - State of the Art review

Assembly

Metrology process models for assembly planning

- Introduces a framework for the creation of metrology process models and their integration with design evaluation and assembly planning.
- Currently, there is a lack of formally defined metrology process models for use within process and assembly planning.
- Recent advances in frameless, large volume metrology enable its positioning as an integral part of the production and assembly technologies and it is thus essential to develop process models to codify its capabilities.
- The process models developed cover large volume metrology systems such as Laser Trackers and iGPS.
- The implemented framework contains functionality that supports:
    - measurability analysis,
    - measurement planning integrated with tolerance and assembly planning,
    - measurement system deployment and
    - metrology assisted assembly automation.
- Initial testing, using aerospace products, demonstrated the effectiveness of the metrology modelling methods.

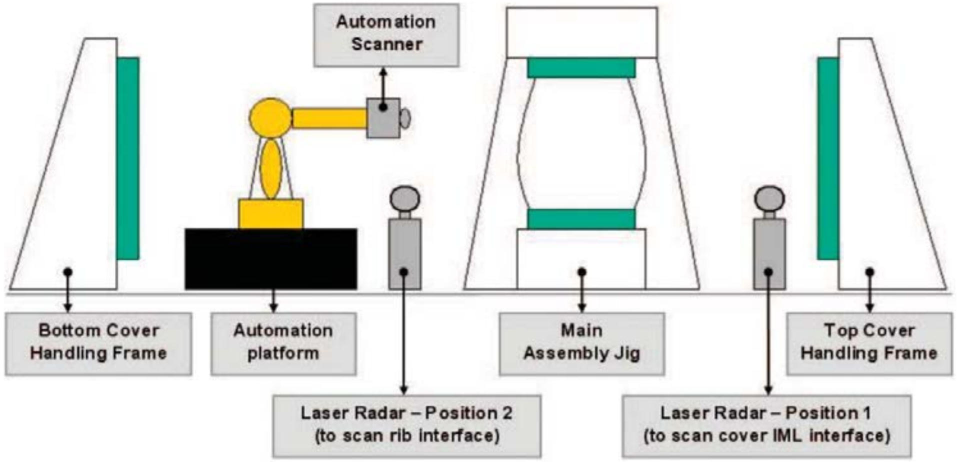




P.G. Maropoulos, Y. Guo, J. Jamshidi, B. Cai, Large volume metrology process models: A framework for integrating measurement with assembly planning, CIRP Annals, Volume 57, Issue 1, 2008, Pages 477-480

Measurement-assisted assembly

- The move towards the automation of manufacturing and assembly processes is a key research area for the aerospace industry.
- The existing integrated robotic systems are often unable to deliver the positioning tolerances required by aerospace products.
- Adaptive control as an enabling technique for robotic system accuracy enhancement has been in the research domain for a few decades.
- The external readings of a metrology system are provided as inputs to the controller of the robotic system in order to compensate for the positioning errors.
- This approach has proved to be more robust than relying only on the internal measures of an operating system.



J Jamshidi, A Kayani, P Iravani, P G Maropoulos, and M D Summers, 2009, Manufacturing and assembly automation by integrated metrology systems for aircraft wing fabrication, Proc. IMechE Vol. 224 Part B: J. Engineering Manufacture

Process control - State of the Art review

Summary and

Segue into the remainder of the session

Summary

- Trends are for more sensors to gather data
- Research looks for multi-level (local, edge and cloud-based) control of disparate physical quantities to manage different levels of the process
  - Latency and synchronisation could become a big issue. 5G the solution?
- Much research is led by “gather any old data, but lots of it, and cross your fingers”
  - From Researchers to CNC manufacturers
- The rapid changes (and ease of creation) lead researchers to aim for self-learning methods, rather than constructing deterministic control models
  - Much validation is on simple cases, lab machines with restricted perturbations
  - Do we need classification of how well a method has been proven?
- More intelligent methods of determining what and where to measure combined with hybrid control models may well be the solution

Presentations in this session

- **Advances in metre traceability for industrial process control**

  Chris Jones – National Physical Laboratory
- **Benchmarking performance for a new rapid machine tool verification process**

  Oliver Martin – Insphere
- **Closed-loop in-process quality improvement: 'Right-first-time' production through digital technologies**

  Dariusz Ceglarek – University of Warwick
- **Robotic machining with embedded feedback**

  Patrick Keogh – University of Bath
- **Flow-front measurement and simulation in liquid composite moulding**

  James Kratz – National Composite Centre

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Process control
State of the Art review

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NPL National Physical Laboratory

The University Of Sheffield.