Reference Systems for a “Free Float” Assembly Setup

IMEKO TC10 Workshop on
Technical Diagnosis in the Cyber-Physical Era

Robert Schmitt
WZL | RWTH Aachen
Fraunhofer IPT

June 6th, 2017

Budapest, Hungary

I – Will Production remain the Same?

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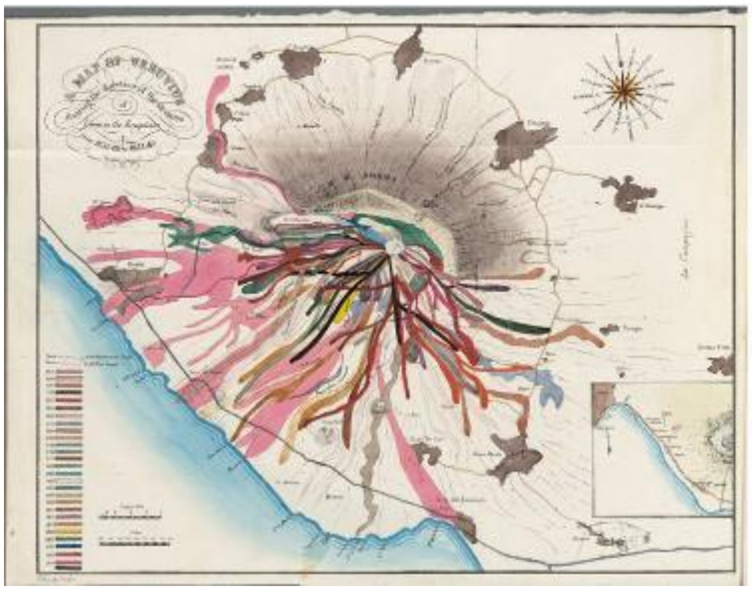
II – Can Metrology contribute to Tomorrow's Production?

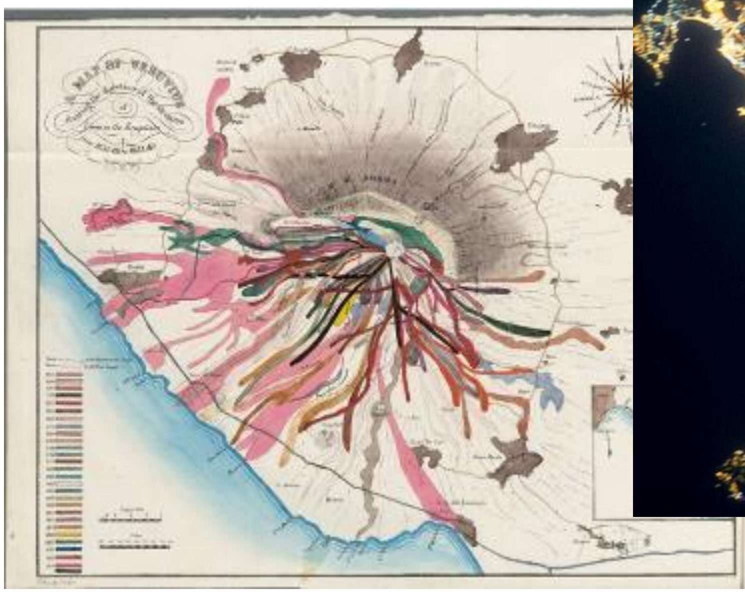
I – Will Production remain the Same?

II – Can Metrology contribute to Tomorrow’s Production?

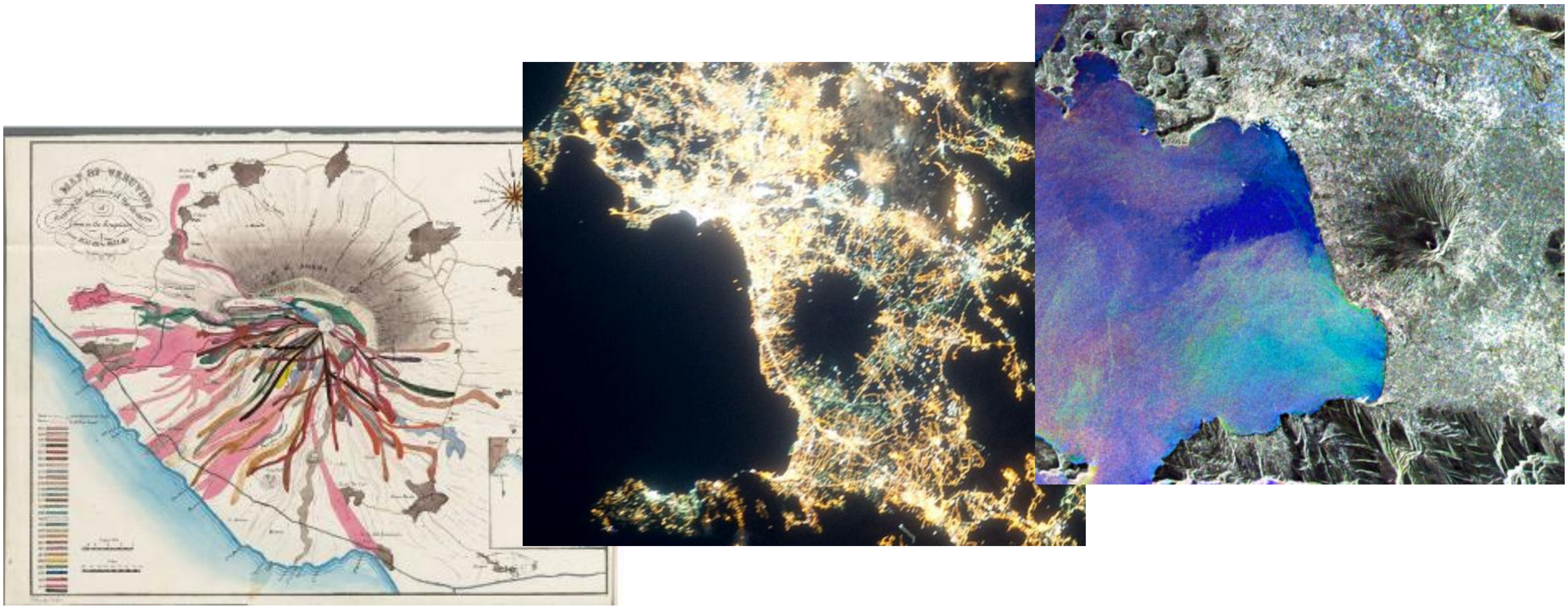
III – What should we assimilate in Tomorrow’s Metrology?



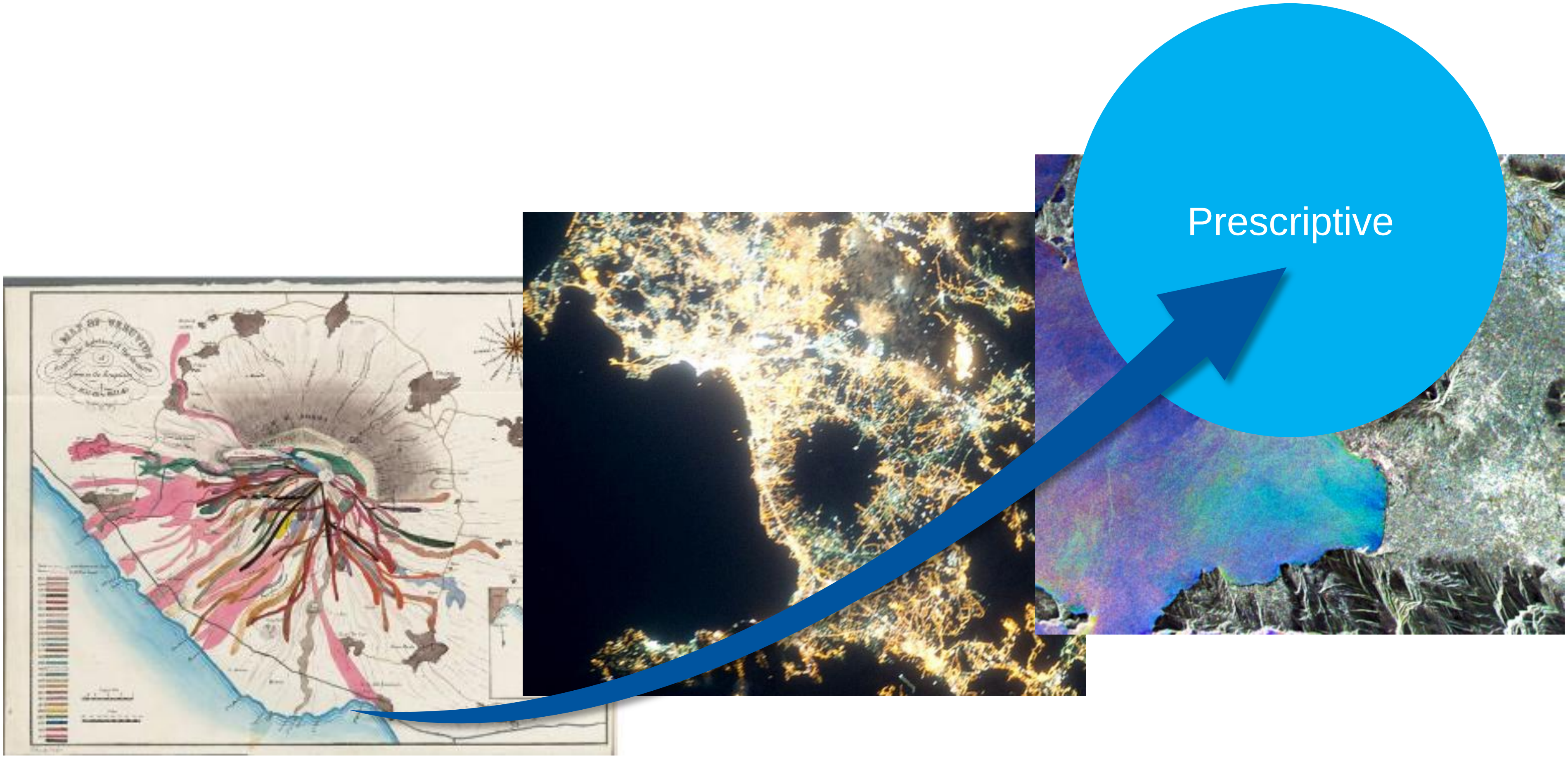
Descriptive



Descriptive -> Diagnostic

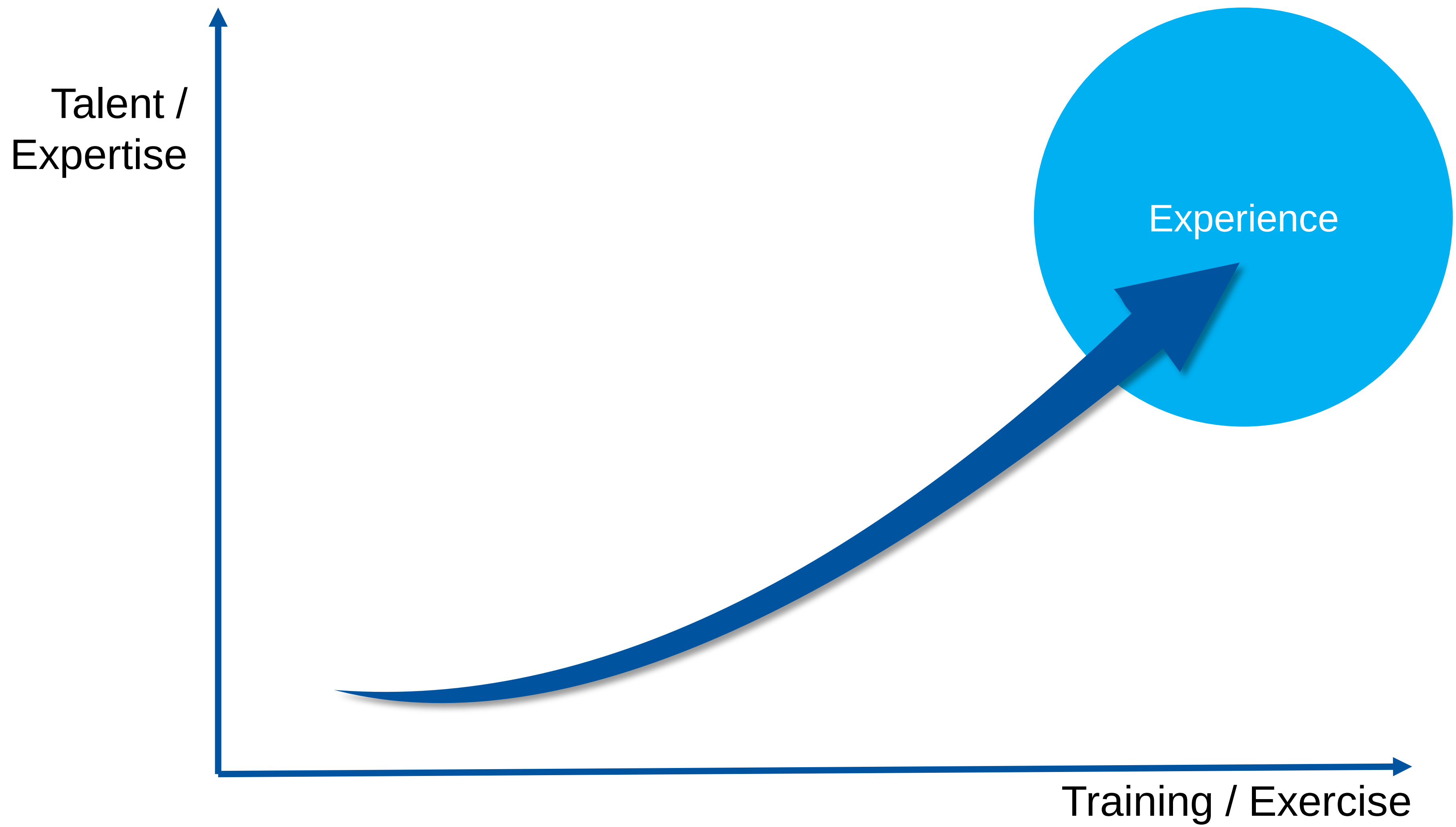


Descriptive -> Diagnostic -> Predictive

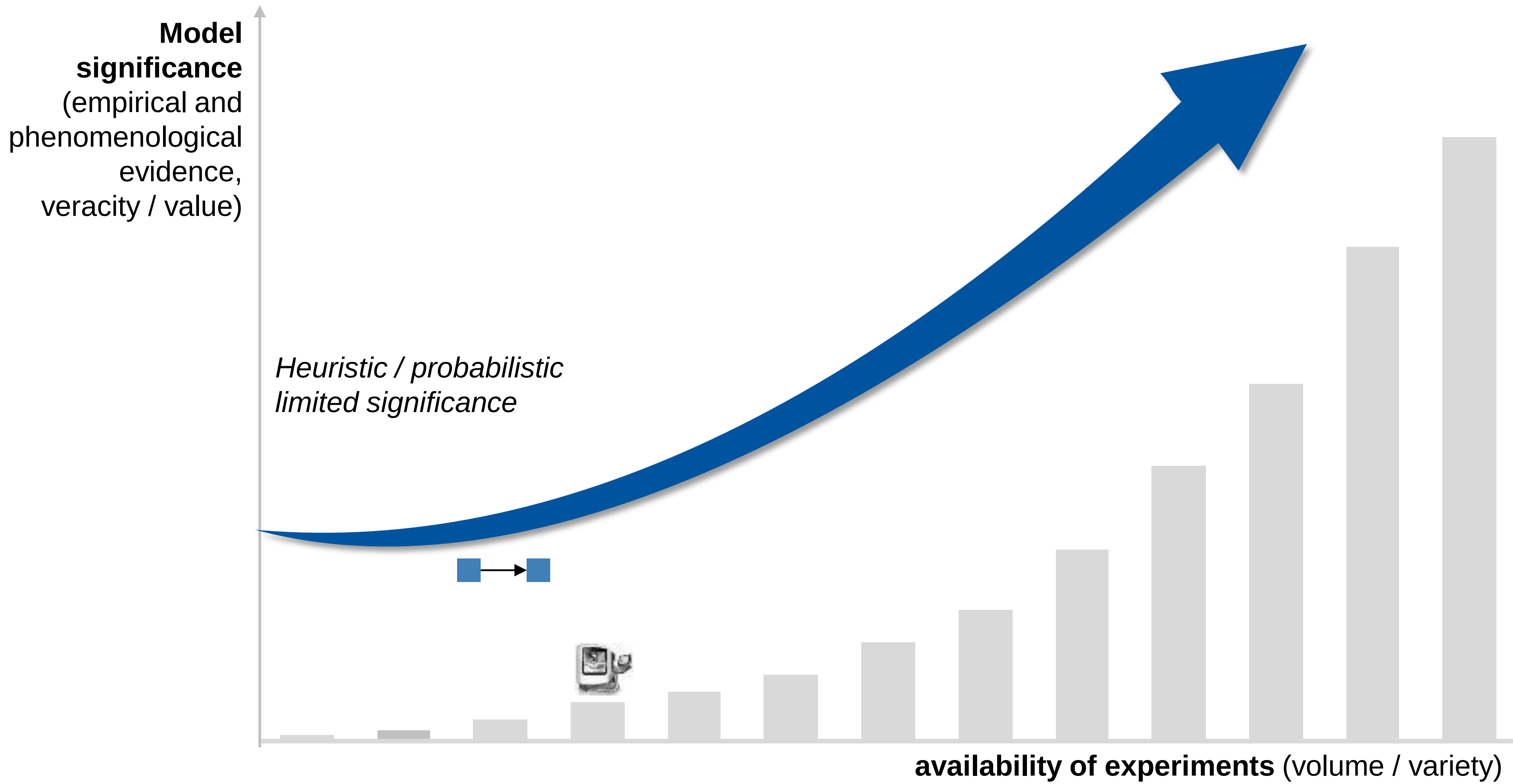


Descriptive -> Diagnostic -> Predictive

Observation:
Experience needs Expertise and Exercise

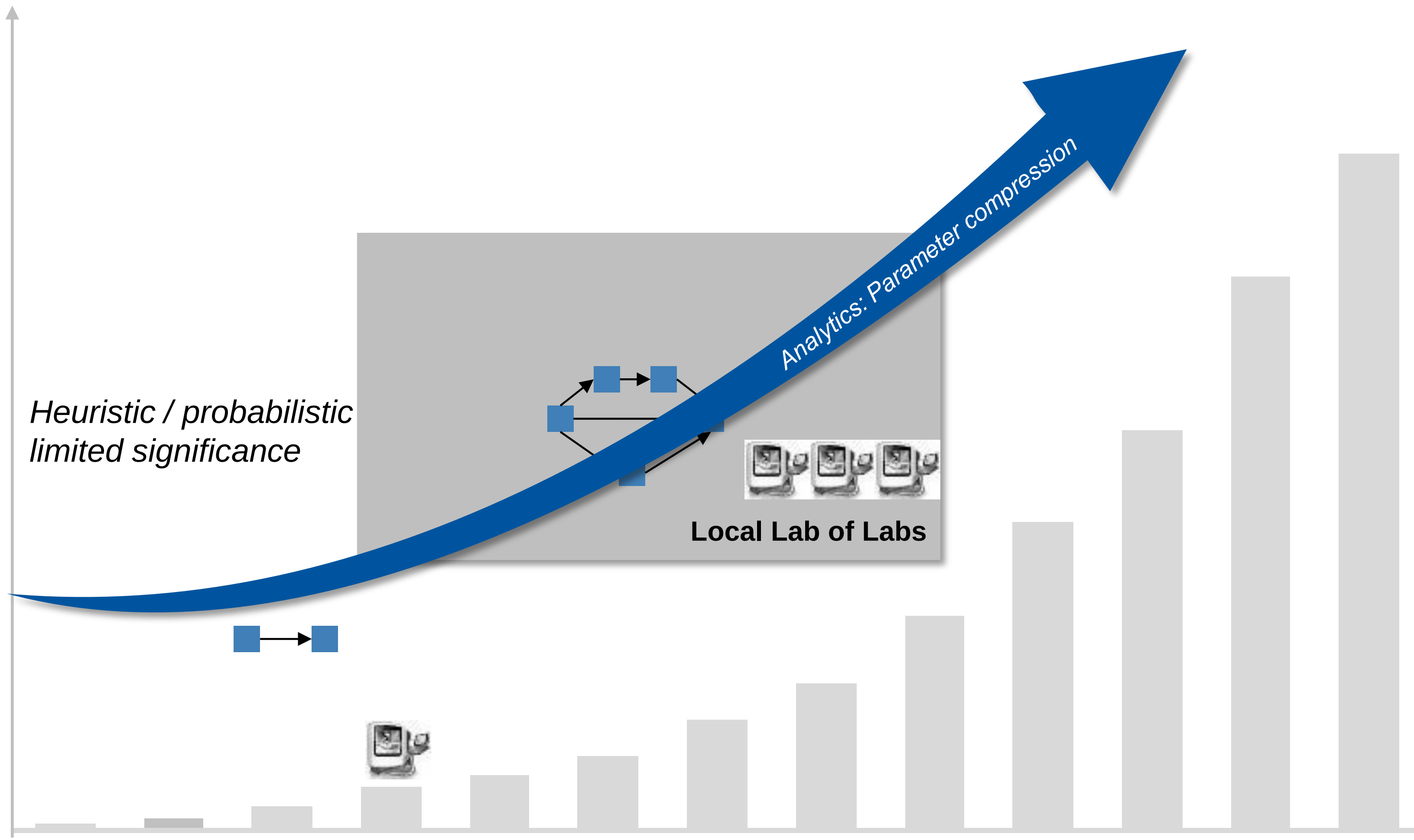


Observation:
The World becomes a Lab



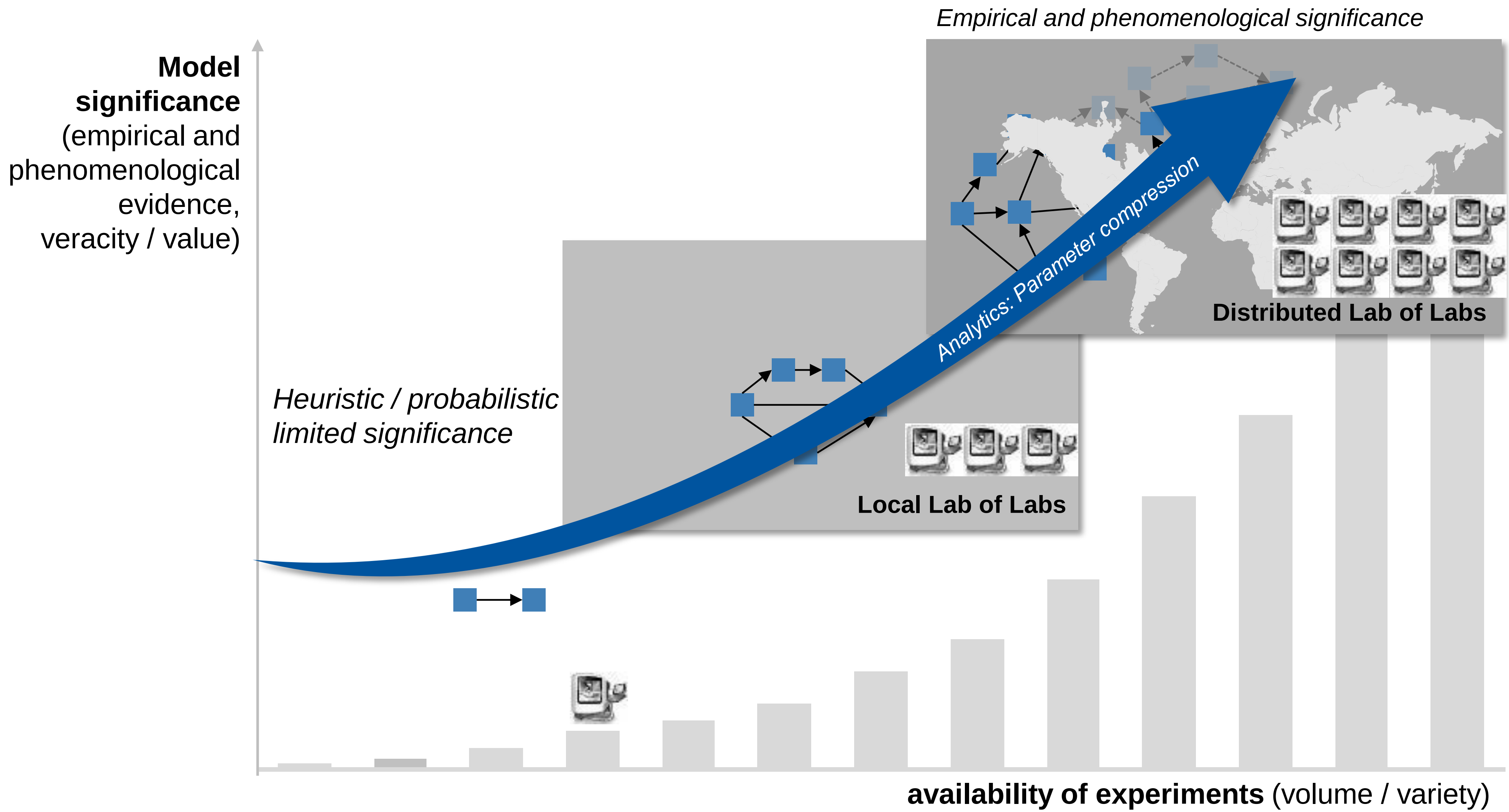
Observation:
The World becomes a Lab

Model significance (empirical and phenomenological evidence, veracity / value)



availability of experiments (volume / variety)

Observation:
The World becomes a Lab



I – A trial on Ontology

New Production Paradigms

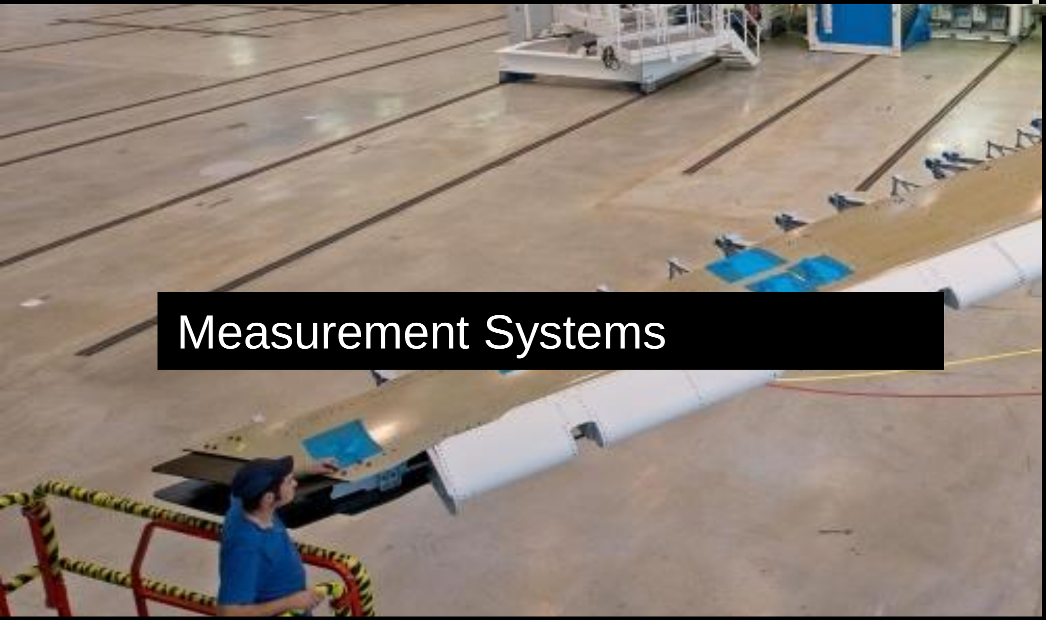
Human-Machine-Interaction

Measurement Systems

Model Based Understanding
of Production

New Production Paradigms

Human-Machine-Interaction

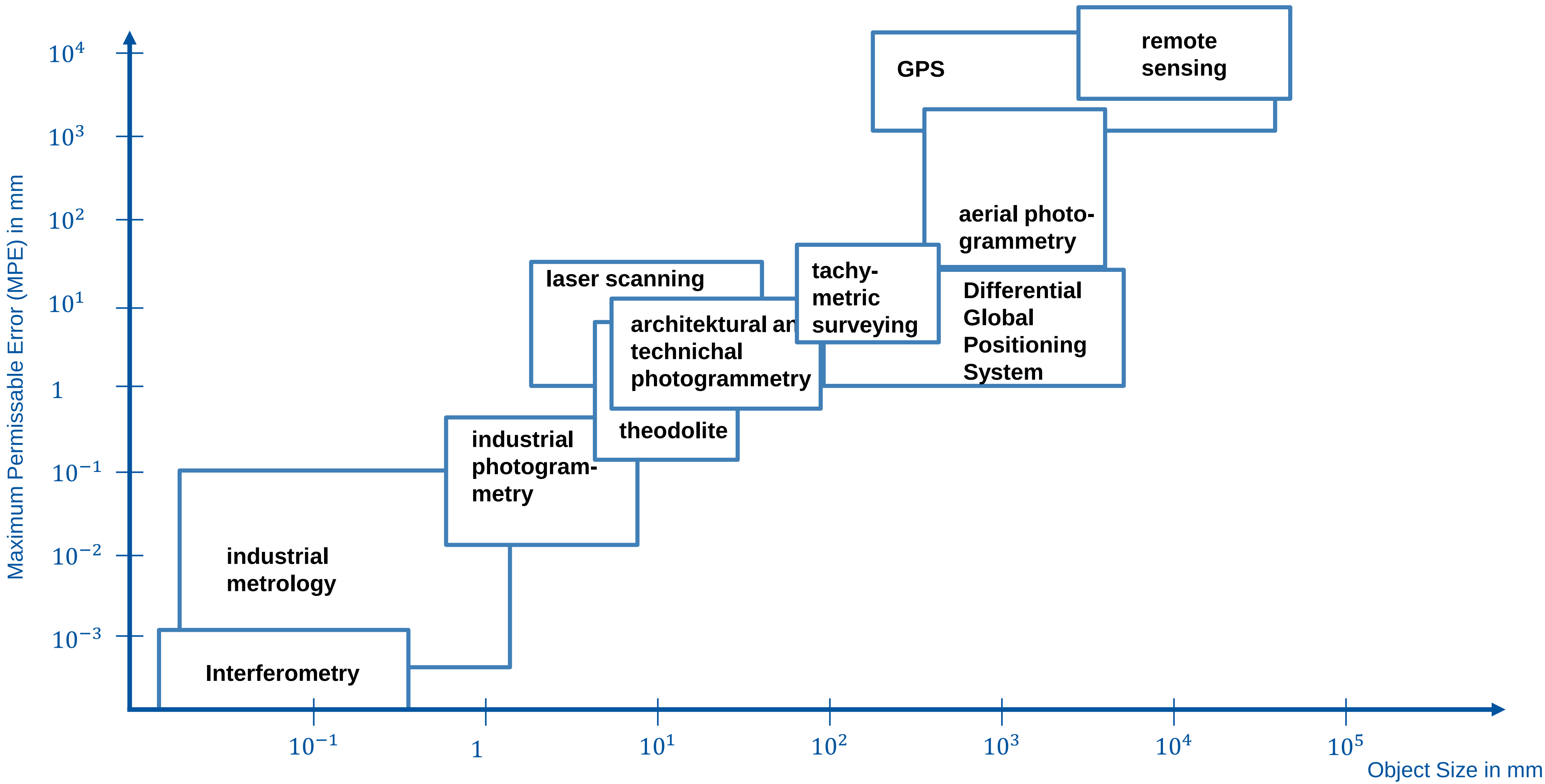


Model Based Understanding
of Production

Receiving Data

AIRBUS

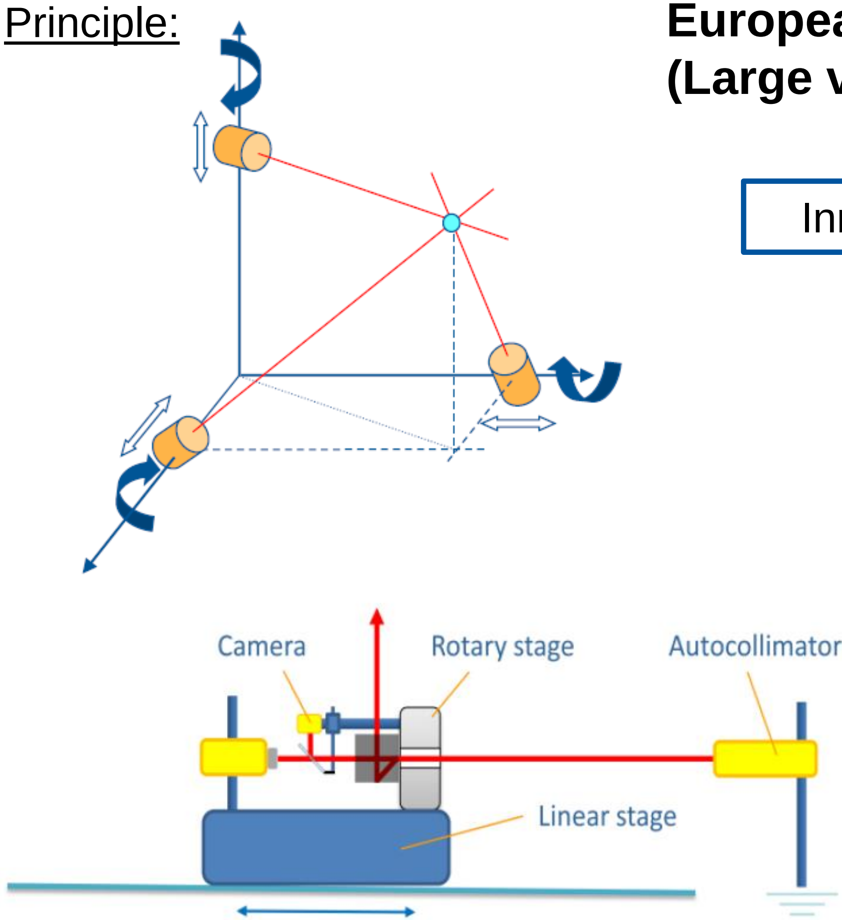
Relationship between Object Size and „Accuracy“ of Measurement Methods



Franceschini, F.: Distributed Large-Scale Dimensional Metrology, Springer, London, 2011, S.4, ISO 10360

1- Innovative 1D Coordinate Measuring System for 3D Measurements
Intersecting Planes Technique (InPlanT)

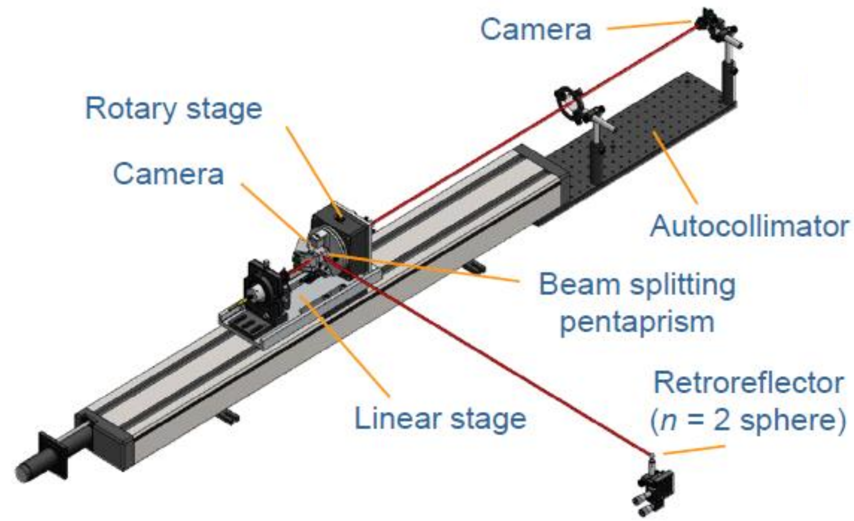
Principle:



European LUMINAR Project
(Large volume Unified Metology for Industry)

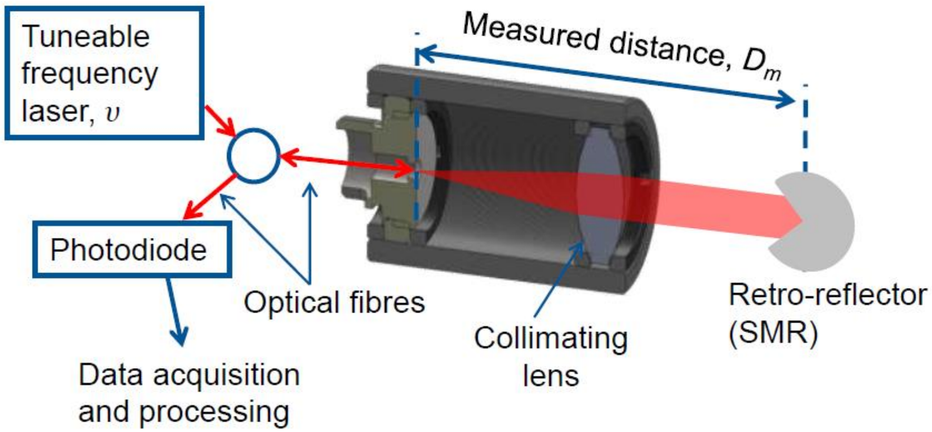
Innovative measuring system working over 10m x 10m x 5m

Prototype:

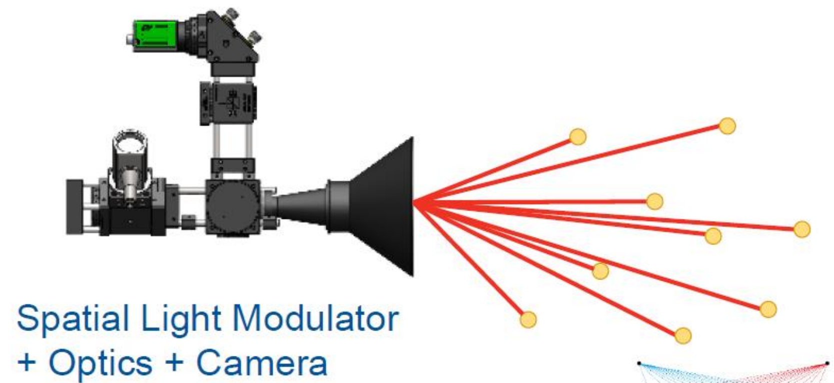


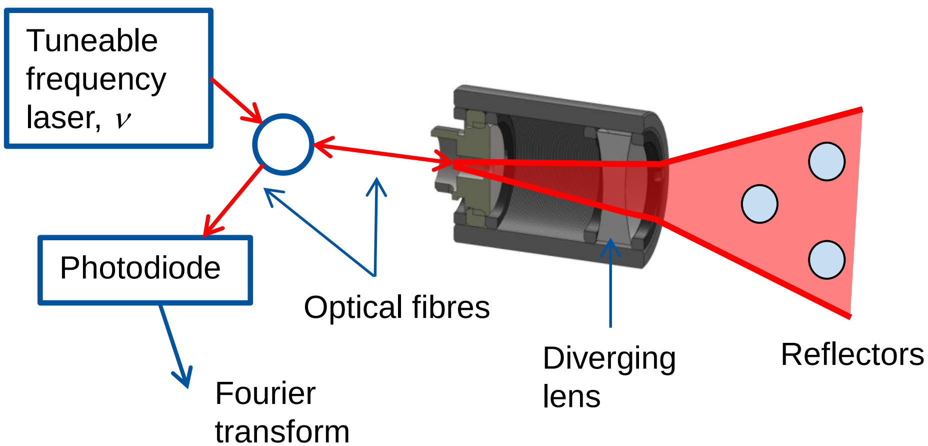
Source:
Balsamo A, Egidi A, Francese C, Pisani M, 1D measurement of coordinates in space: a novel apparatus, euspen 2016, May 2016, Nottingham, UK
Pisani M, Balsamo A, Francese C, Cartesian approach to large scale co-ordinate measurement: InPlanT, LMPMI, September 2014, Tsukuba, Japan

2 - Absolute Interferometry
Divergent beam and Long range FSI



Innovative measuring system working over 10m x 10m x 5m



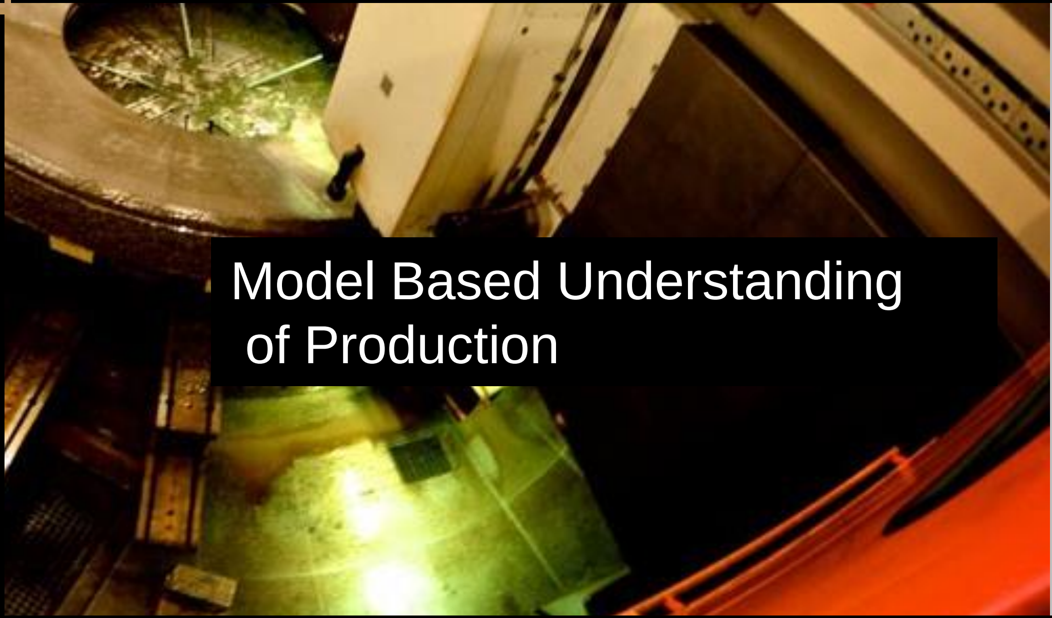


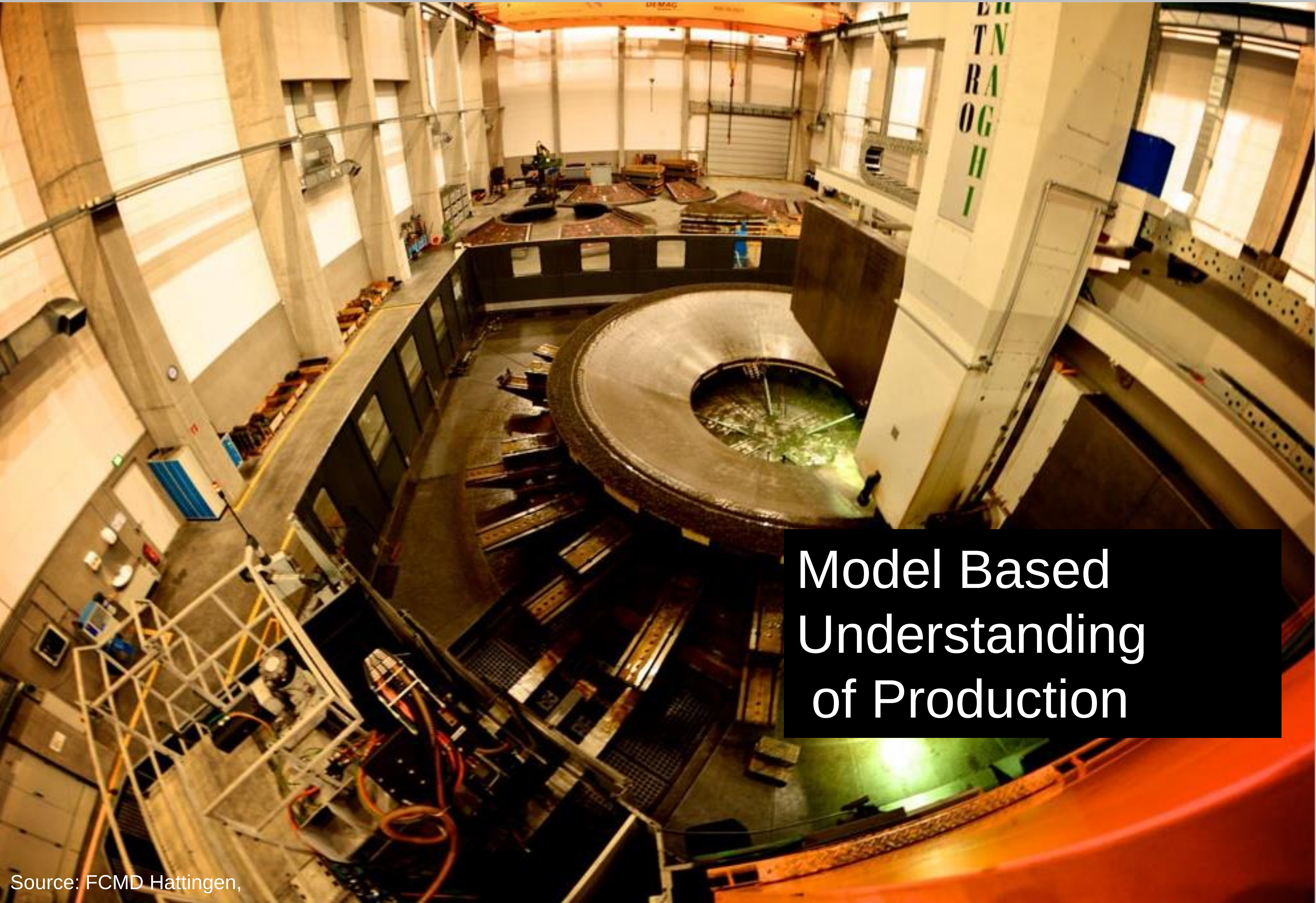
Source: Campbell M, Hughes B, A high-accuracy, self-calibrating and traceable coordinate measurement system, euspen 2016, May 2016, Nottingham, UK

New Production Paradigms

Human-Machine-Interaction

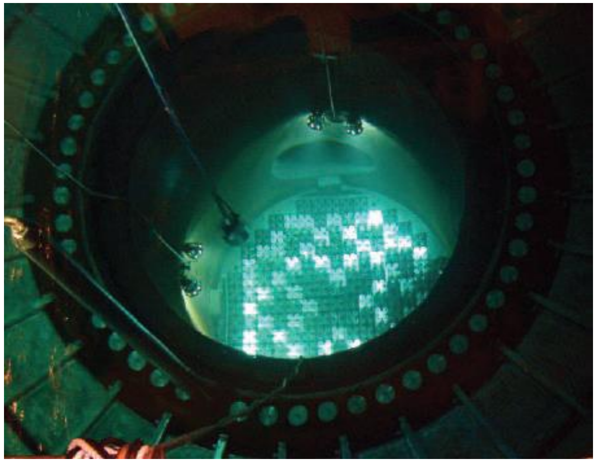
Measurement Systems



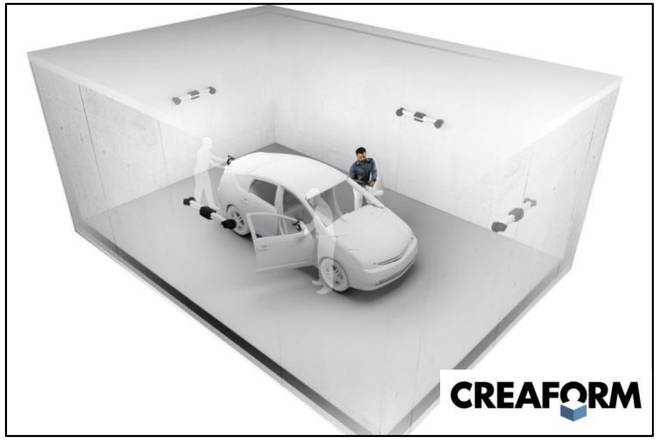


Source: FCMD Hattingen,

Refractive index compensation for LSM applications
Light-based Measurement Systems and Temperature



Nuclear fuel assemblies



Car body inspection

Modelling of human movements for computer games

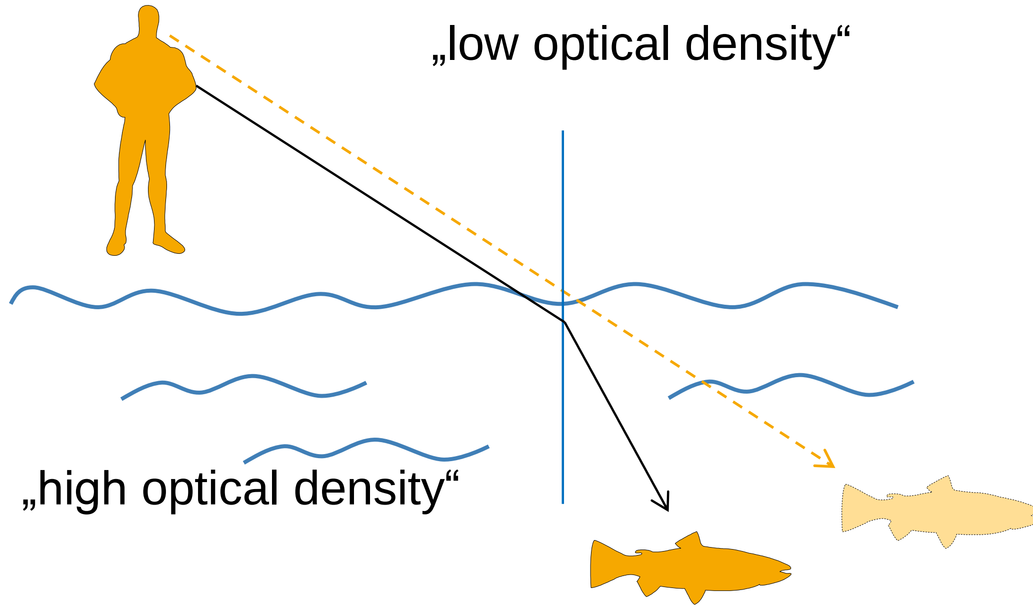
General assume that light travels in straight lines but thermal effects in particular cause light rays to bend.

This could be a problem in factories, e.g. where air is cold on the floor and warm under the roof.

Source:
Robson S, Kyle S, MacDonald L, Shortis M, Towards understanding photogrammetric refraction in large volume metrology, LVMC, November 2014, Manchester, UK
Robson S, MacDonald L, Kyle S, Shortis M, Close range calibration of long focal length lenses in a changing environment, ISPRS 2016, July 2016, Prague, Czech Republic

Refractive index compensation for LSM applications

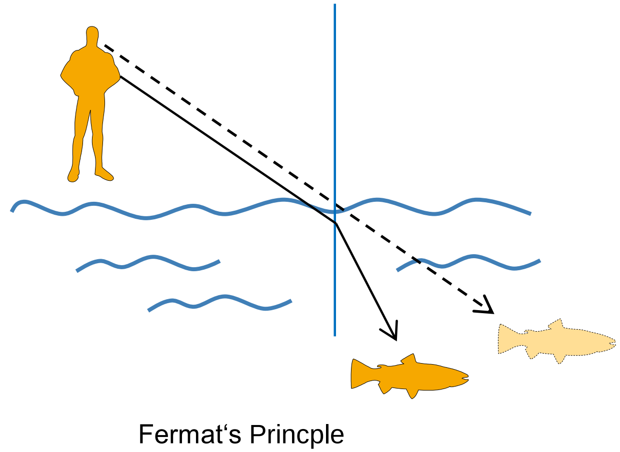
Struggeling with Fermat's Principle in Optical Systems

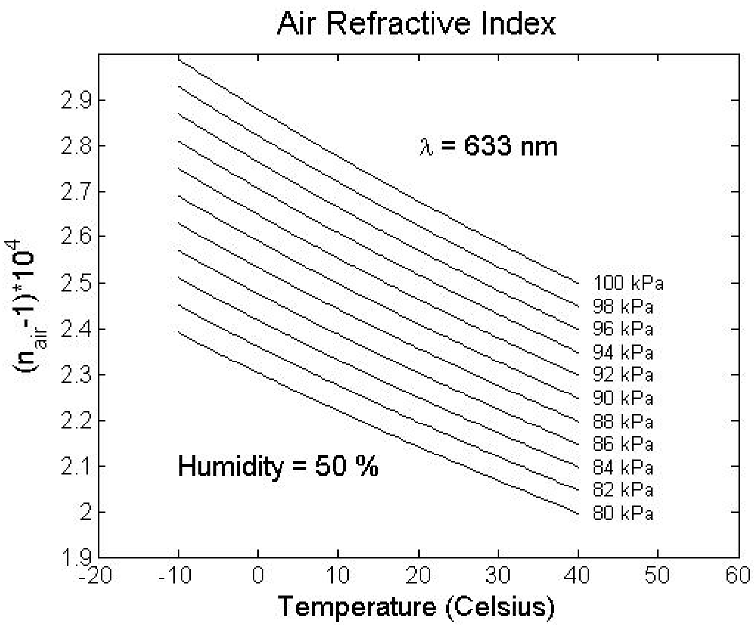


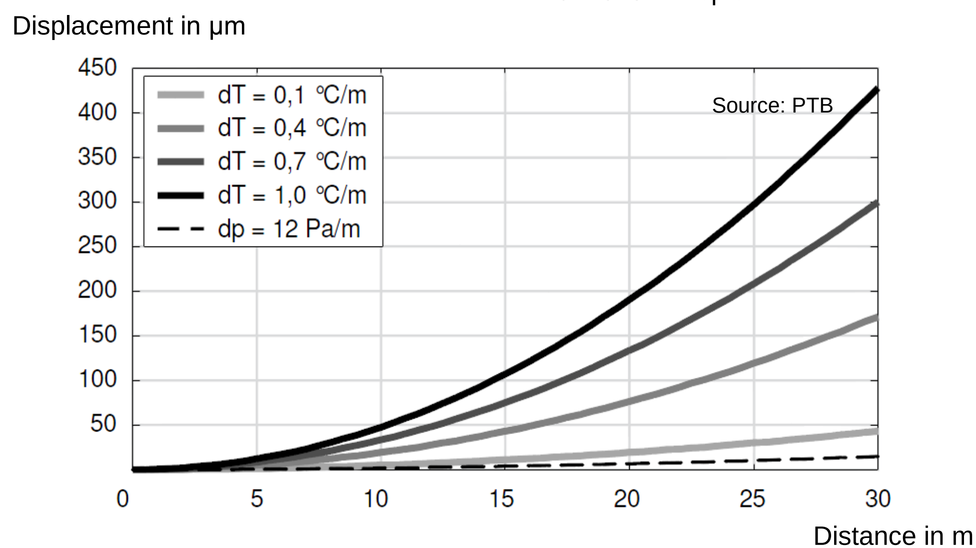
Refractive index compensation for LSM applications
Why we need the exact refractive index…

– laser wavelength = vacuum wavelength/refractive index

– "School"	air ref. index	= 1
– "University"	air ref. index	= 1.000 3
– "NMI"	air ref. index	= 1.000 276 (15 °C and 1 atm)
–		= 1.000 266 (25 °C and 1 atm)



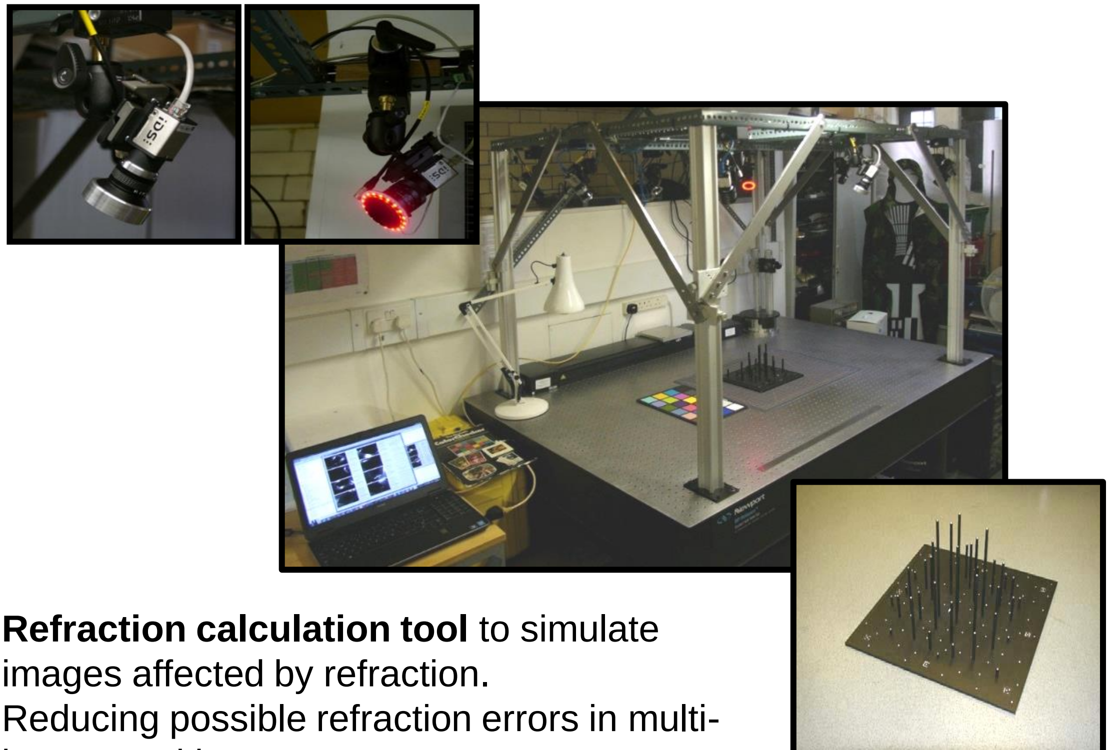




Source:
Robson S, MacDonald L, Kyle S, Shortis M, Close range calibration of long focal length lenses in a changing environment, ISPRS 2016, July 2016, Prague, Czech Republic
John A. Smith, CIRES, University of Colorado at Boulder

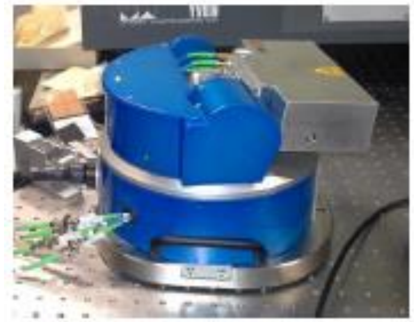
Model-based Refractive Index Compensation

Photogrammetry



Refraction calculation tool to simulate images affected by refraction.
Reducing possible refraction errors in multi-image tracking.

Interferometry



Refractive index compensation by two colour interferometry

IFM mode: frequency doubled Nd: YAG laser (1064 nm+532 nm)

IFM measurement 1d uncertainty
$\mathrm{U} = \sqrt{(1\mu m)^2+(10^{-7}l)^2}$

Source:
Robson S, Kyle S, MacDonald L, Shortis M, Boehm, J. Multi-camera systems for dimensional control in factories, EPMC, November 2015, Manchester, UK
Robson S, MacDonald L, Kyle S, Shortis M, Close range calibration of long focal length lenses in a changing environment, ISPRS 2016, July 2016, Prague, Czech Republic
Meiners-Hagen K, Pollinger F, Prellinger G, Rost K, Wendt K, Pöschel W, Dontsov D, Schott W, Mandryka V, Refractivity compensated tracking interferometer for precision engineering, IWK Ilmenau, September 2014, Ilmenau, Germany

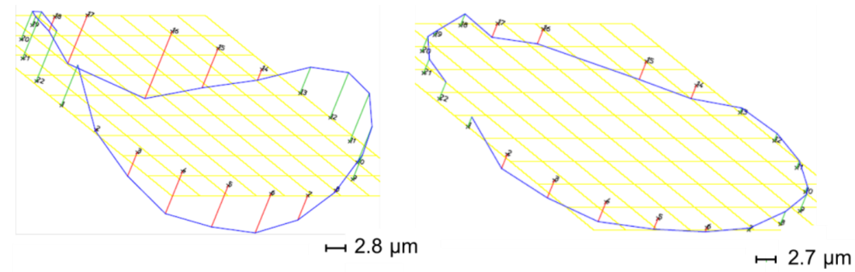
Models for workpieces under thermal and gravitational load (1/2)

EMRP Project ENG 56 “Drivetrain”

Traceable measurement of drive train components for renewable energy systems

DriveTrain

Involute gear standard and extra stiff coupling for measuring process



Deviation neg.:
Deviation pos.:
Real value: ***

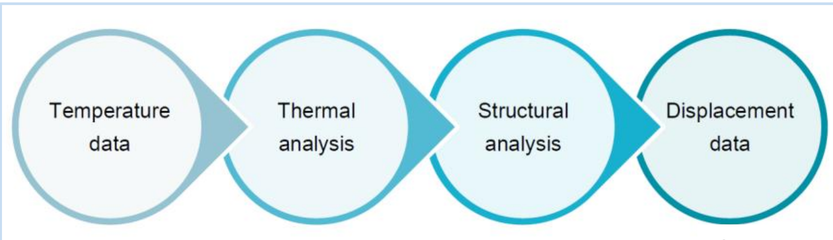
Deviation neg.:
Deviation pos.:
Real value: ***

Flatness measurement carried out on the upper reference plane of a ring gear 3-point support (left), 4-point support (right)

Sources:

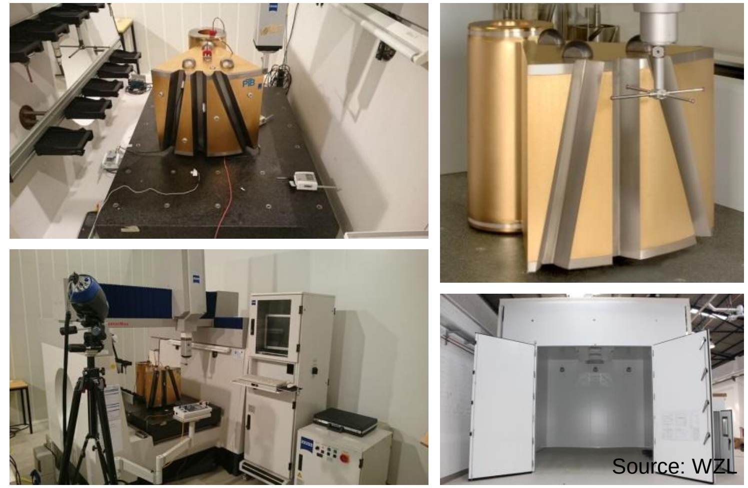
M. Stein, K. Kniel, F. Härtig: Reliable Measurements of Large Gears, presented at AGMA FTM 2014, October 2014 USA
M. Deni, G. Picotto: Traceable Measurements of Drivetrain Components for Renewable Energy Systems, presented at Gear Forum, March 2015, Italy
R. Schmitt, M. Peterek, Traceability in Large-Scale Metrology - Modeling Thermal Effects of Large DriveTrain Components, presented at EPMC European Portable Metrology Conference, November 2015, UK

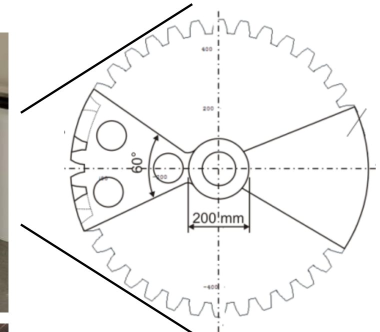
Models for workpieces under thermal and gravitational load (2/2)



Source: NPL

General steps for model based analysis from temperature data to displacement prediction for thermal compensation

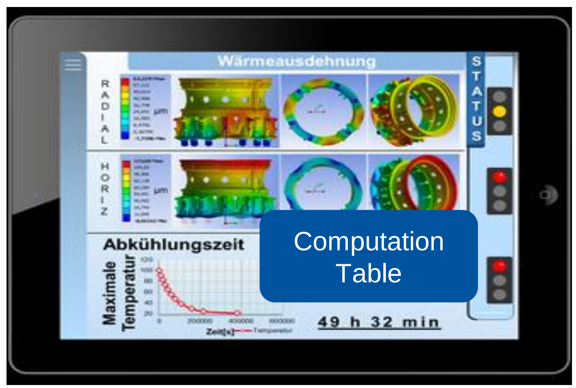




Workpiece, initial temperature

Ambient temperature curve

Material properties



Thermalisation time

Approximate temp. distribution (t)

Approximate, feature-specific thermal expansion and displacement (t)

Source:
R. Schmitt, M. Peterek, Traceability in Large-Scale Metrology - Modeling Thermal Effects of Large DriveTrain Components, presented at EPMC European Portable Metrology Conference, November 2015, UK

New Production Paradigms

Human-Machine-Interaction

Measurement Systems

Model Based Understanding
of Production

New Production Paradigms

CPPS as a solution to the main challenges in Assembly

CPPS …

consist of autonomous and cooperative elements and subsystems that are getting into connection with each other in situation dependent ways, on and across all levels of production, from processes, through machines and production systems, up to production and logistics networks…

- directly **acquire physical data by using sensors** and **act on the physical world by using actors**
- **analyse and store the acquired data** and **interact both with the physical and the virtual world**
- are networked amongst each other and within global information systems by wired or wireless communication means
- use worldwide available data and services,
- dispose of several multi-modal human-machine-interfaces.

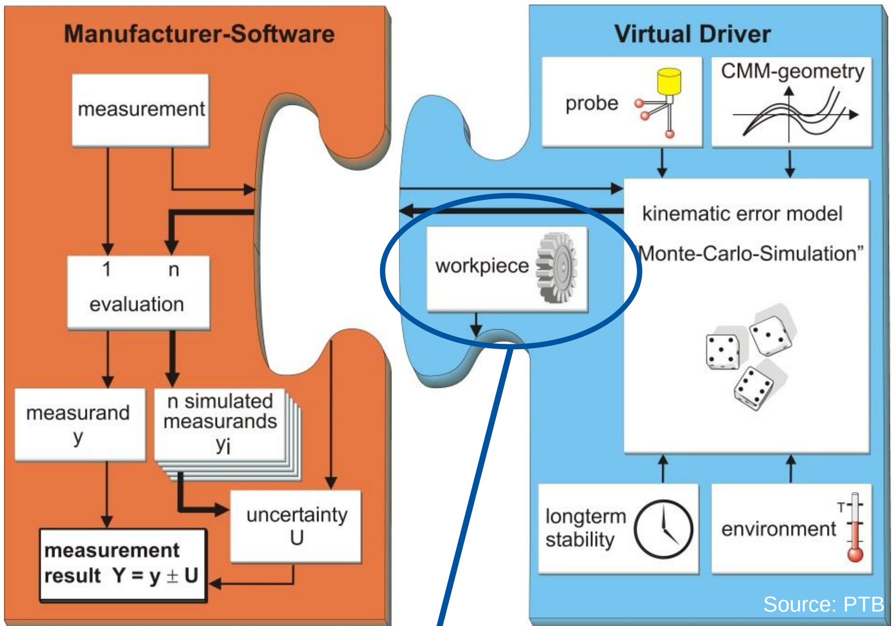
Models for **measurement-systems** and **workpiece** allow the prediction of the interaction between both in the **virtual measurement process** (VMP)!

Virtual instruments and virtual measurement systems

Task

Automatic determination of the measurement uncertainty by simulation (numerical experiment) with the virtual Coordinate Measuring Machine (vCMM).

Adaption of the principle for the virtual Laser Tracker (vLT)

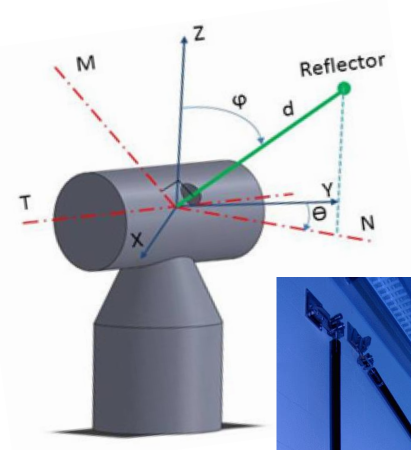


Priciple of vCMM

Large-scale parts: Modelling of thermal and gravitational behaviour is important!

Principle

- modelling the measuring process
- determination of
  - machine characteristic
  - measuring conditions
  - workpiece
- collecting and distorting measuring points by Monte Carlo simulation
- evaluating several up to thousand measuring results
- calculating the measurement uncertainty

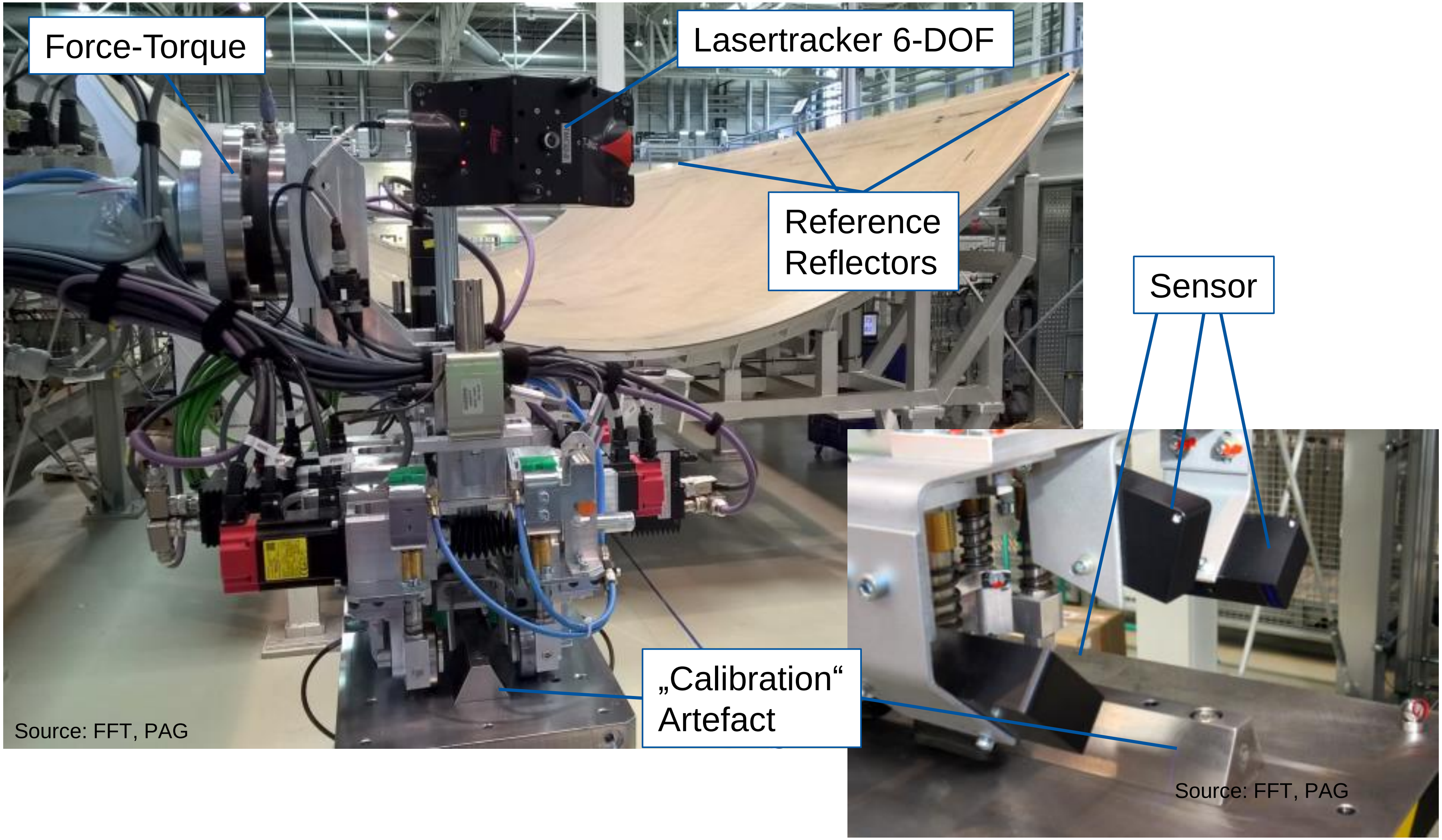


LaserTracker and reference wall at PTB in Braunschweig

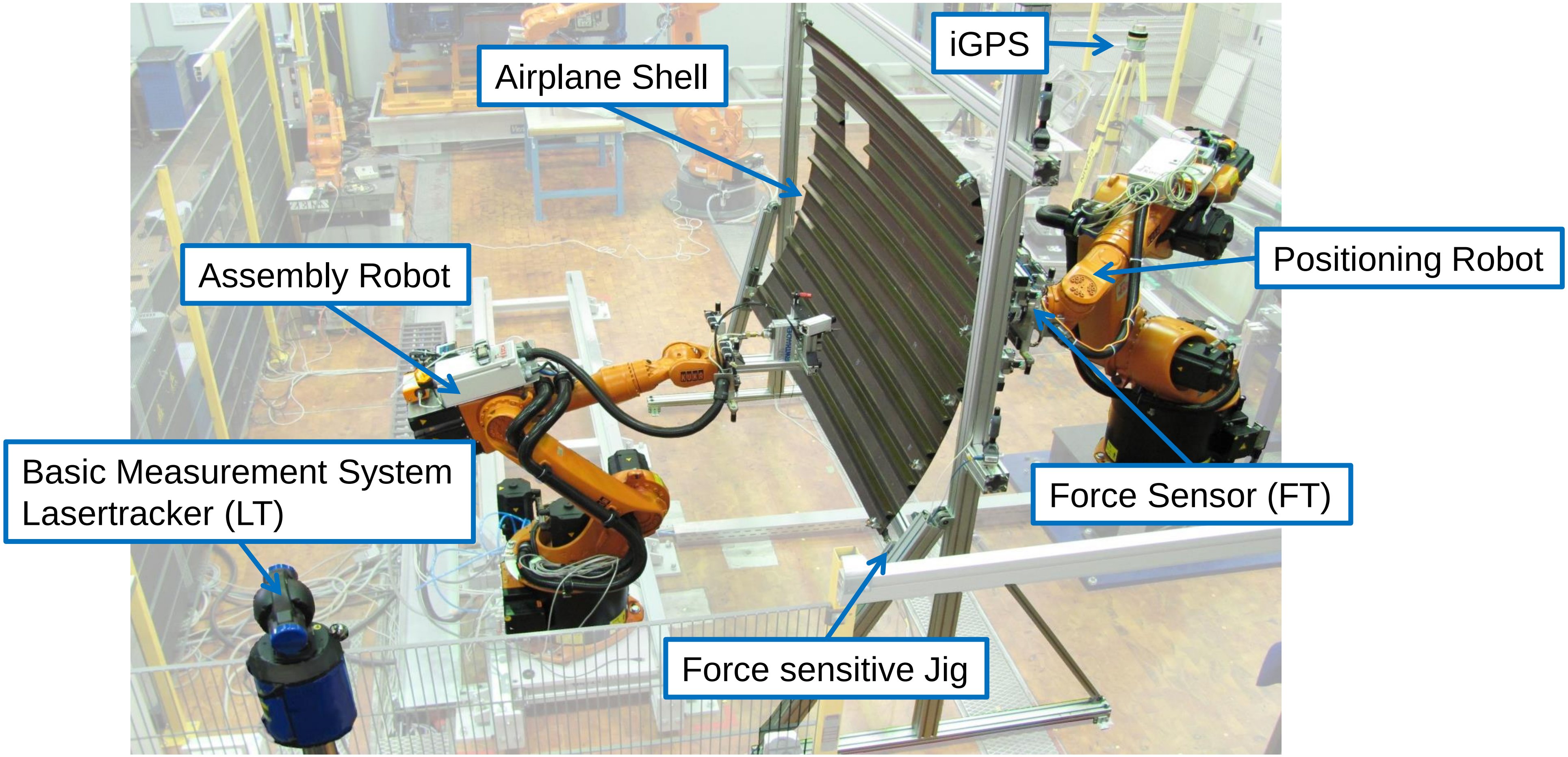
Sources:
Muralikrishnan, B., Phillips, S., Sawyer, D., Laser Trackers for Large Scale Dimensional Metrology: A Review, Precision Engineering 44 13 (2016)
Ulrich T, Uncertainty Estimation for Kinematic Laser Tracker Measurements, IEEE Explore, 2015

Multi Sensor Architecture

Towards a Metrology based Reference System

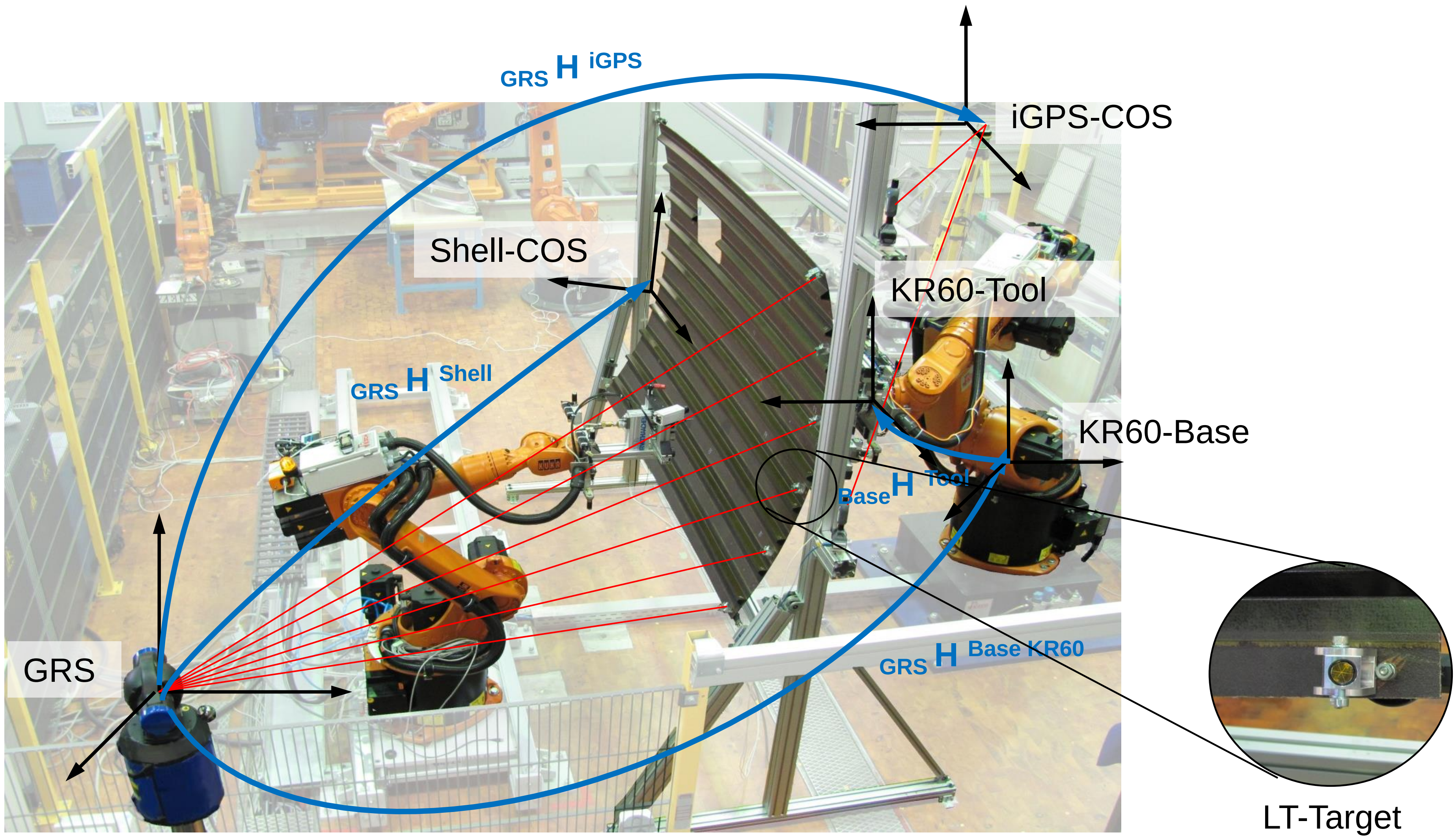


Use Case: Robot Assisted Adjustment of Airplane Shell
Communication network for system entities



Use Case: Robot Assisted Adjustment of Airplane Shell

Different Local coordinate systems



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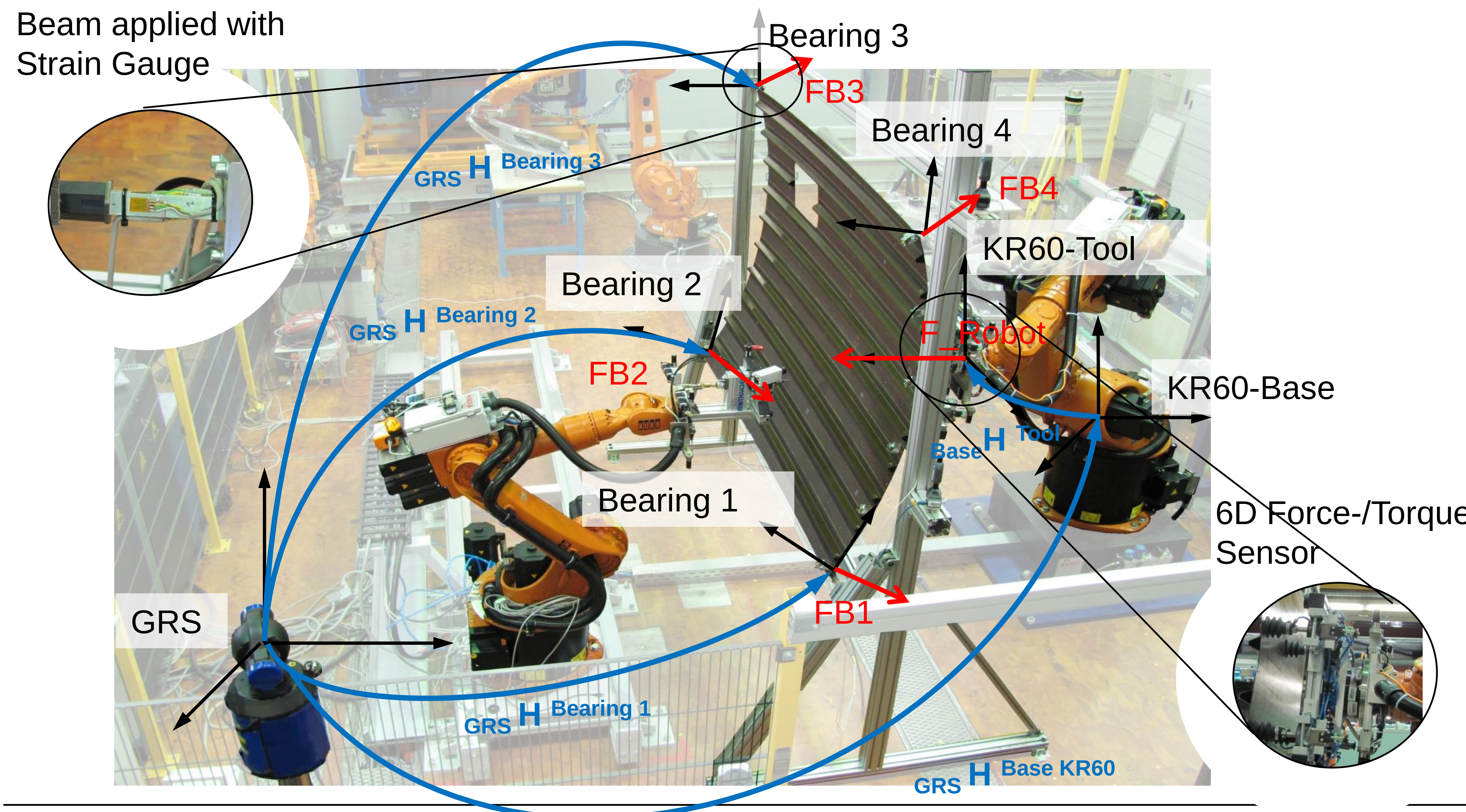
Use Case: Robot Assisted Adjustment of Airplane Shell

Force Vectors



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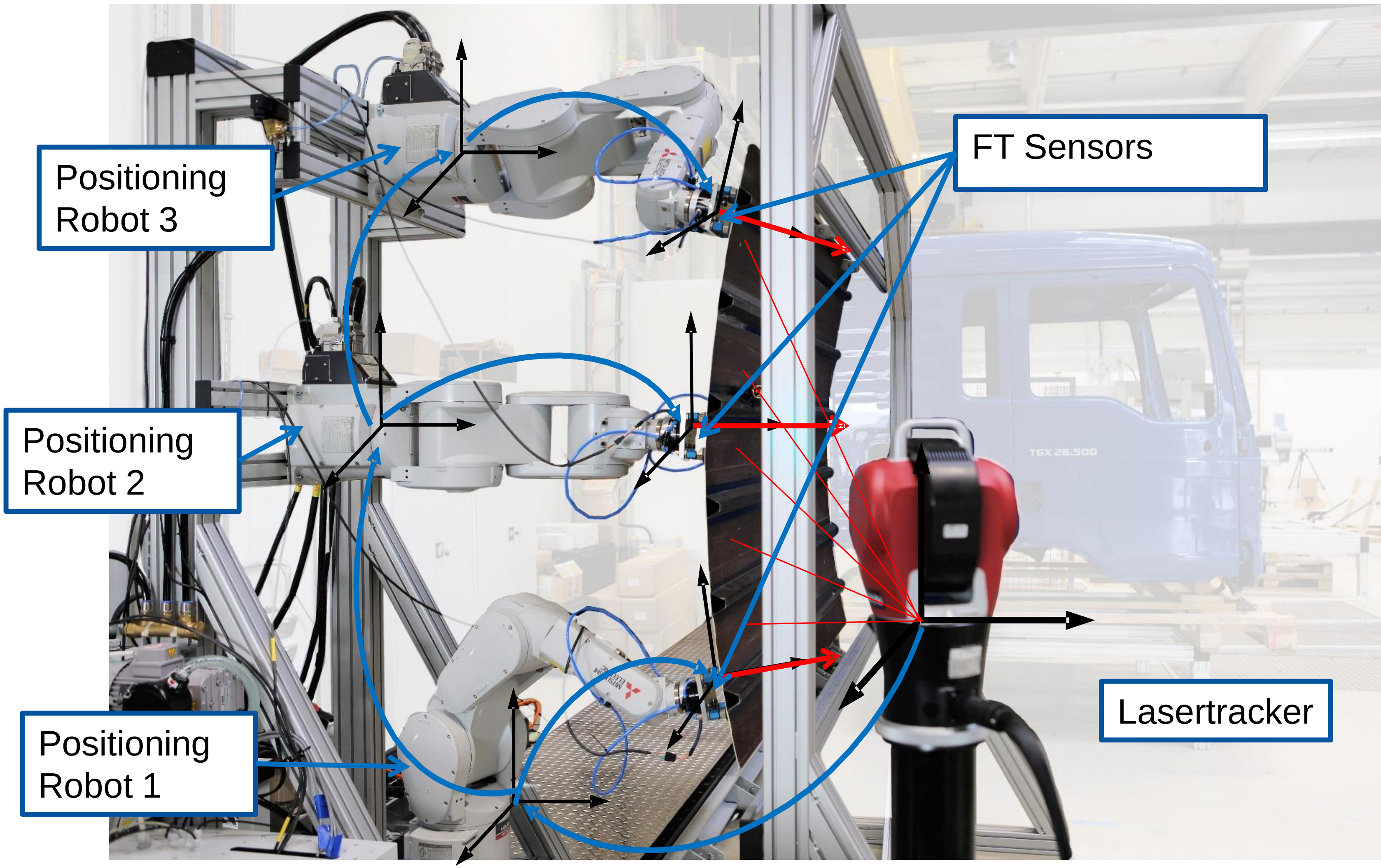
Use Case: Robot Assisted Adjustment of Airplane Shell

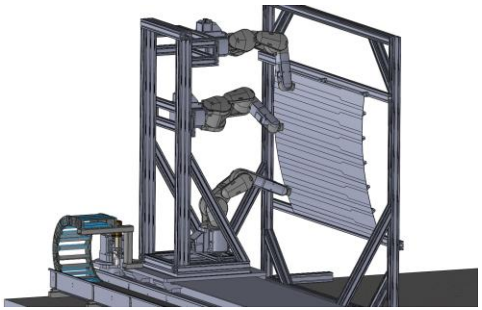
Set-up



Cyberphysical Production Systems
Linking Real and Virtual World for Large-Scale Assembly

„Virtual World“

Simulation and Control

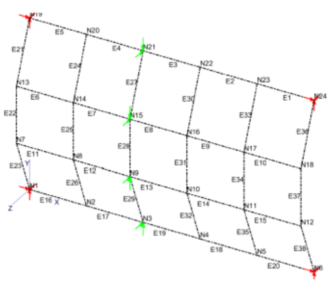


Parameter

- Position for robots
- Valid forces
- Path planning

Informationupdate

Model-based analysis of data

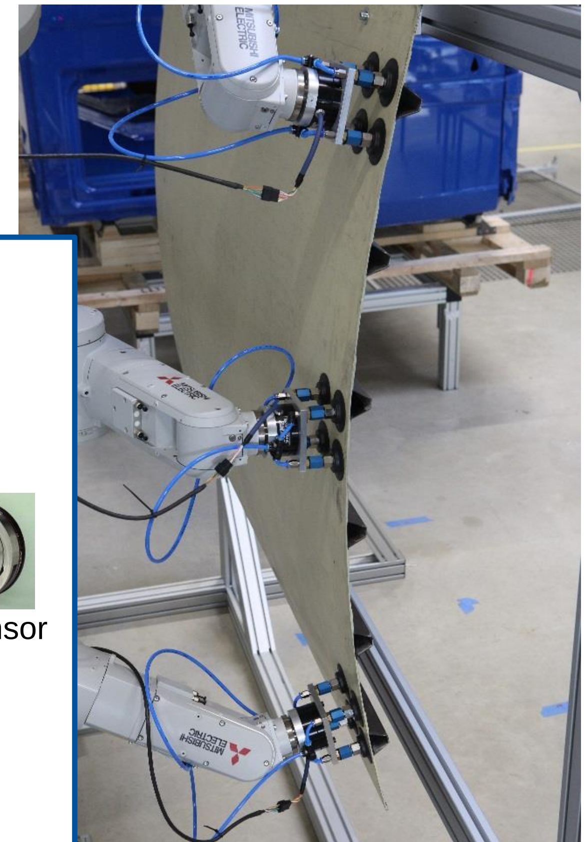


Modell
- MSA
- Parameters from real world data

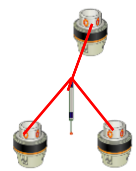
Data

- Position
- Geometry
- Forces

„Real World“



Sensors



iGPS

FT-Sensor

Lasertracker

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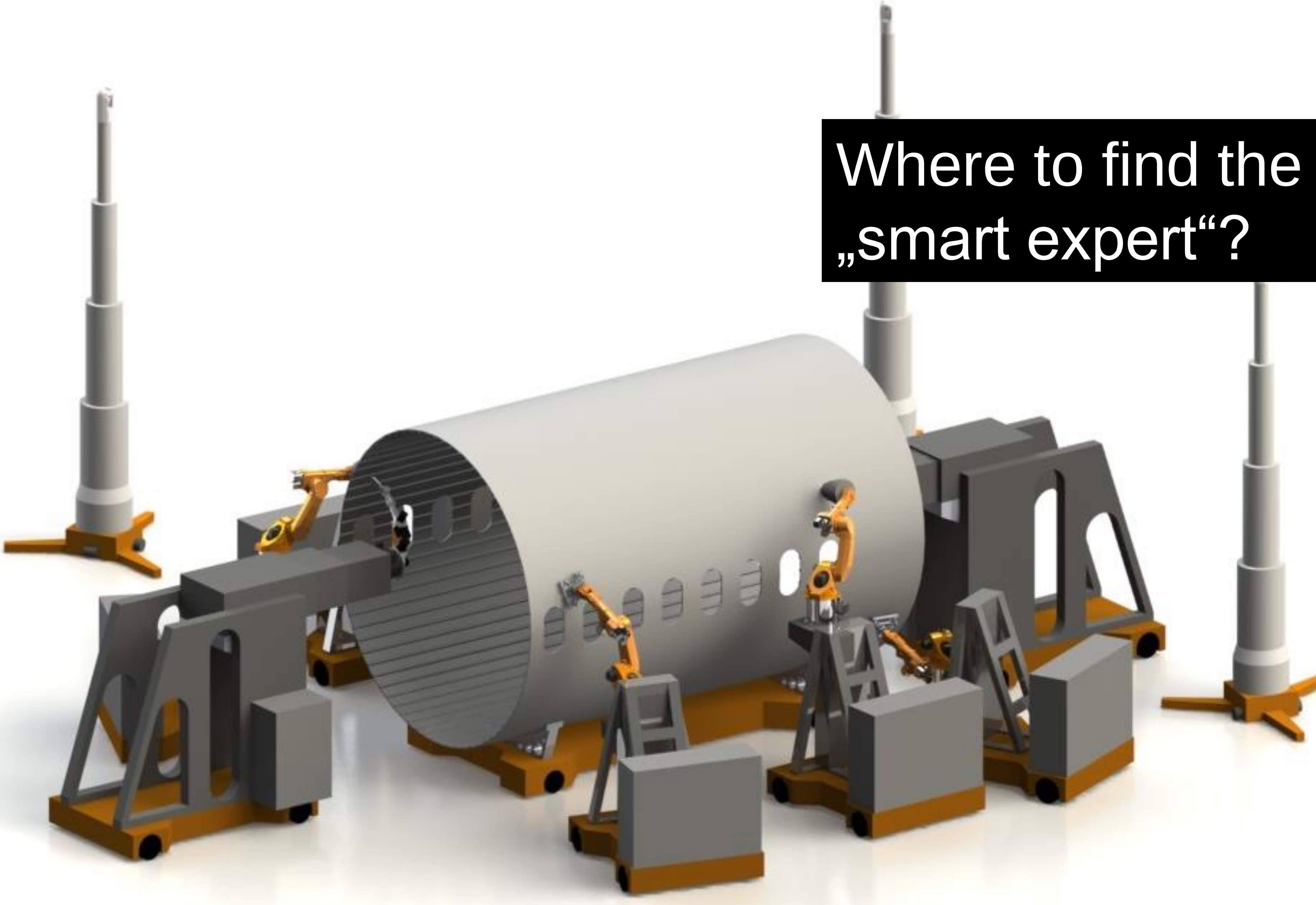
Measurement Systems

Model Based Understanding of Production



Where to find the „smart expert“?

Example Process: Assembly of Truck Windscreen and Cabin

Navigation e. g. UWB	■ The truck cabin is transported on a mobile platform ■ Low requirements regarding measurement uncertainty, but data needs to be permanently available
Assembly e. g. iGPS	■ The windscreen is mounted to the truck cabin ■ The measurement uncertainty must be suffiently low in order to avoid a tolerance mismatch of the overall process
Inspection, e. g. Laser-Tracker	■ Optionally critical sections of the cabin can be checked after the assembly process ■ The measurement uncertainty needs to be significantly lower (1 order of magnitude) than the tolerance to allow reliable inspection

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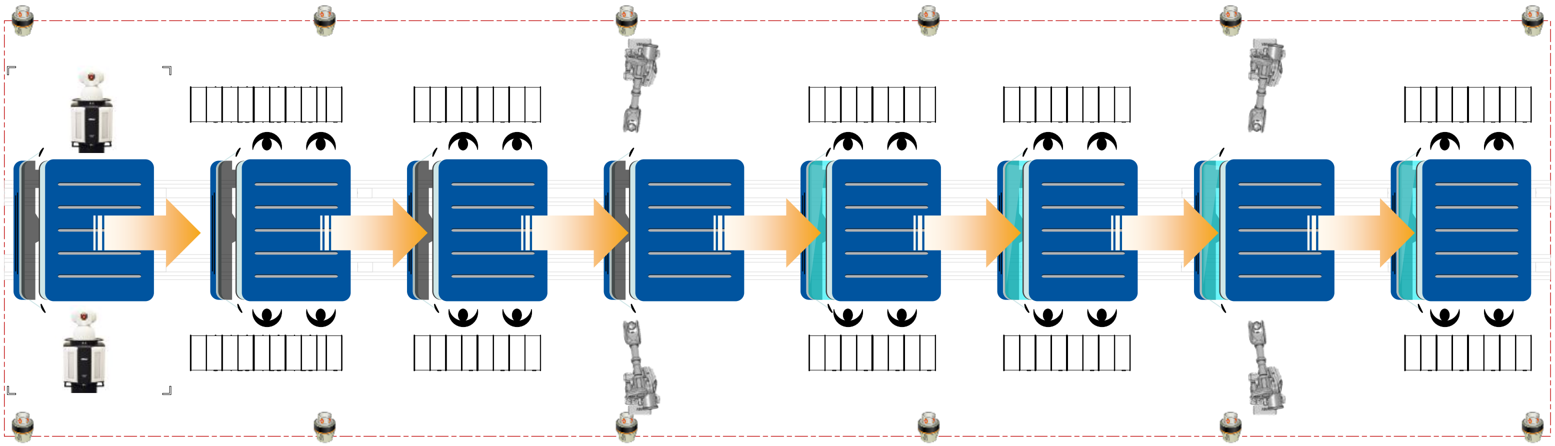
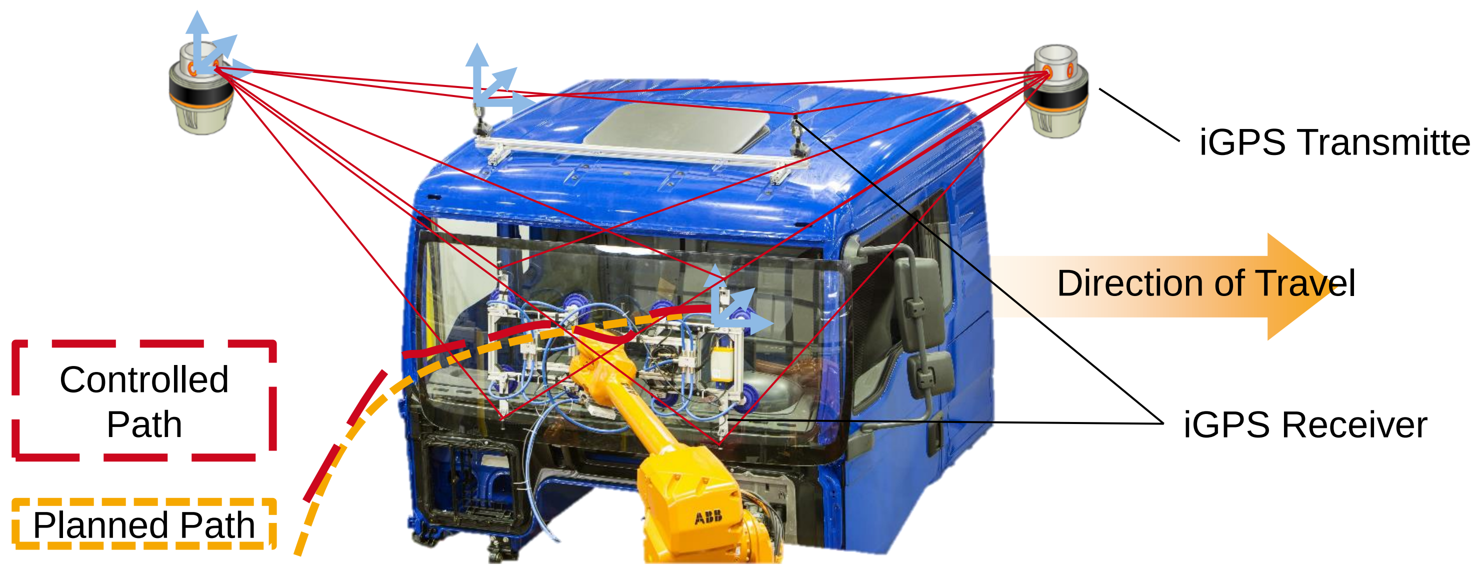
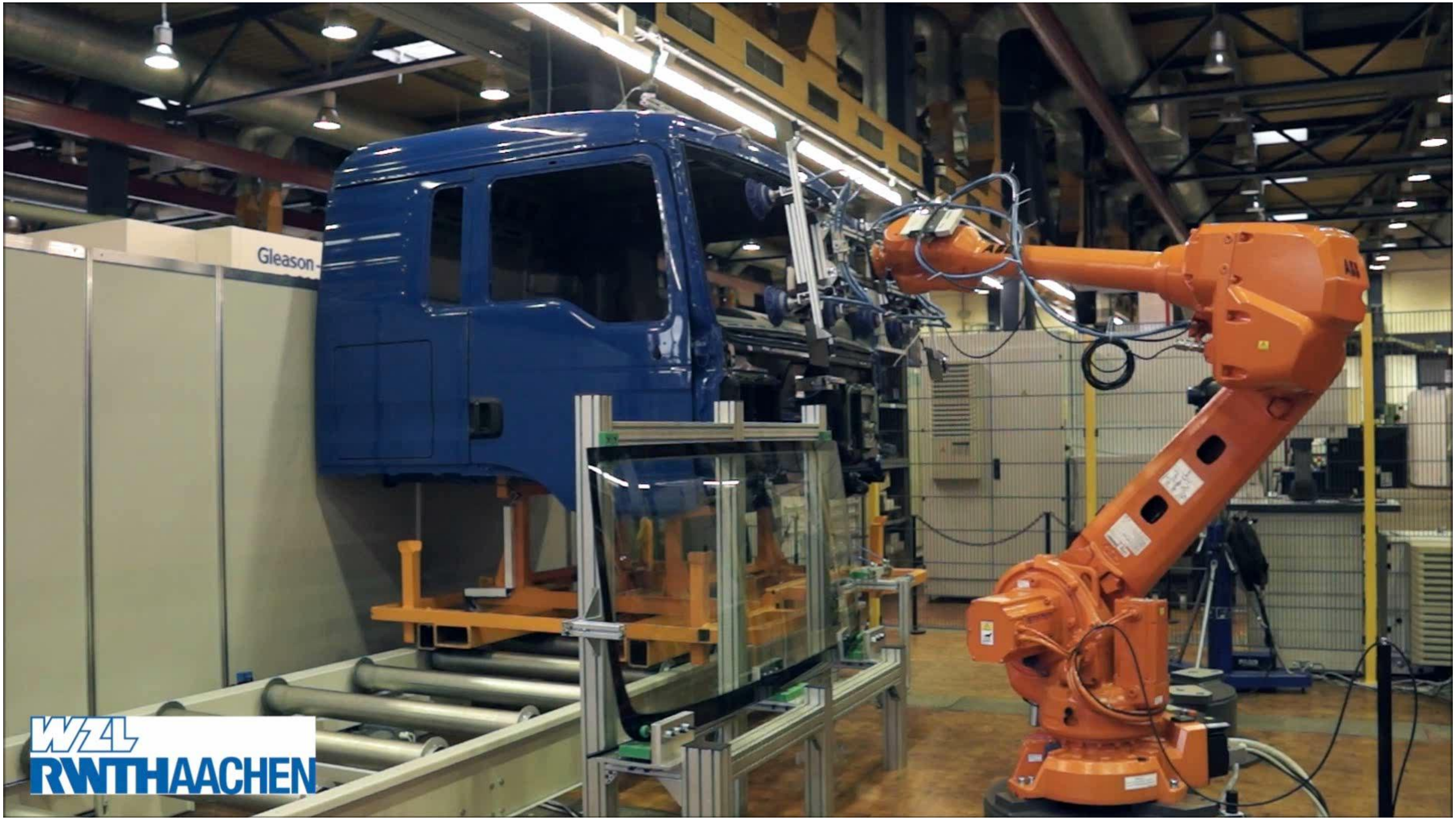
Assembly of Large Components in Motion



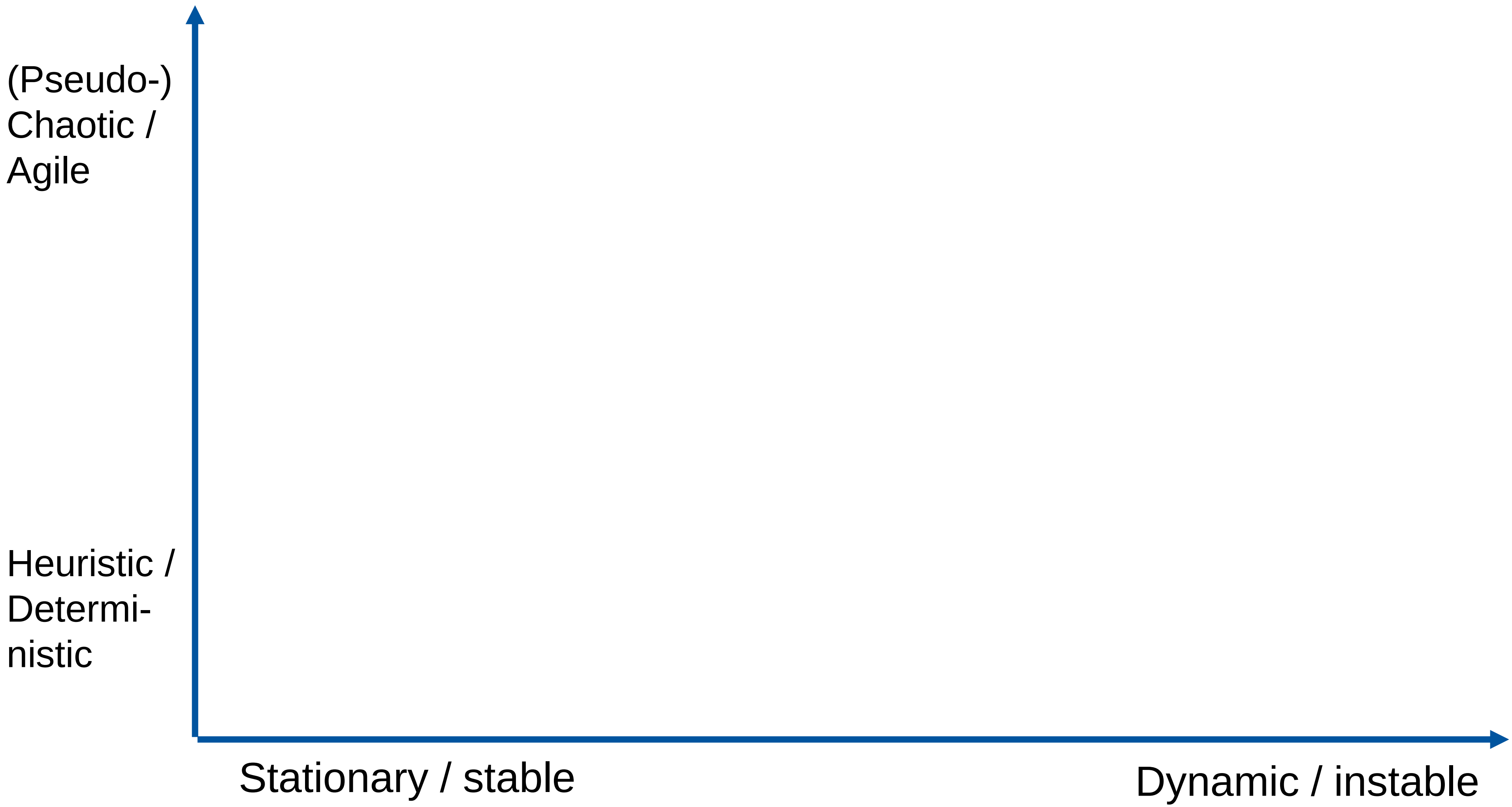


Assembly of Large Components in Motion



II – Same Metrology as ever?

Self-stabilizing control loops no longer match production needs



Self-stabilizing control loops no longer match production needs

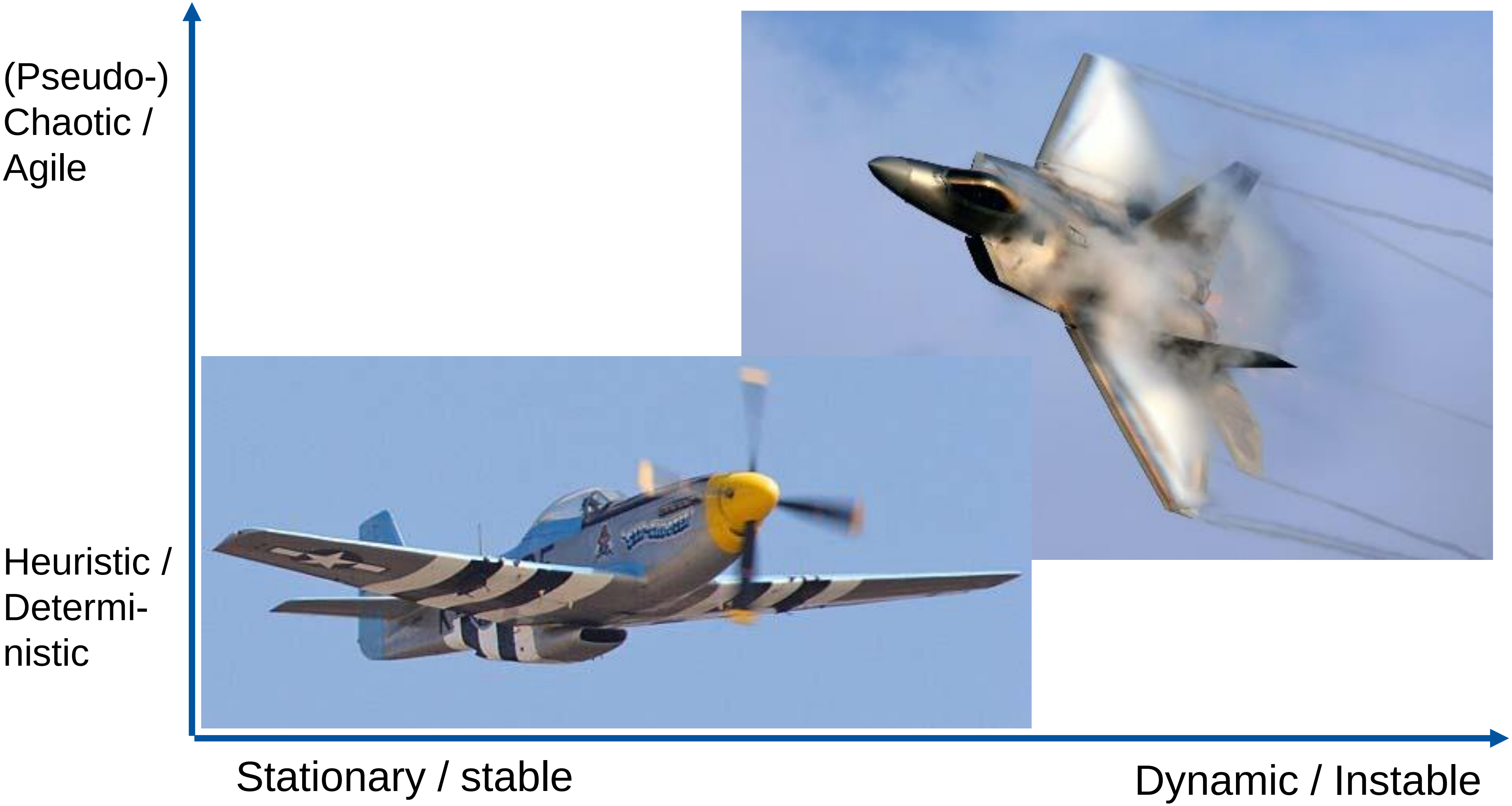
(Pseudo-) Chaotic / Agile

Heuristic / Determi-nistic

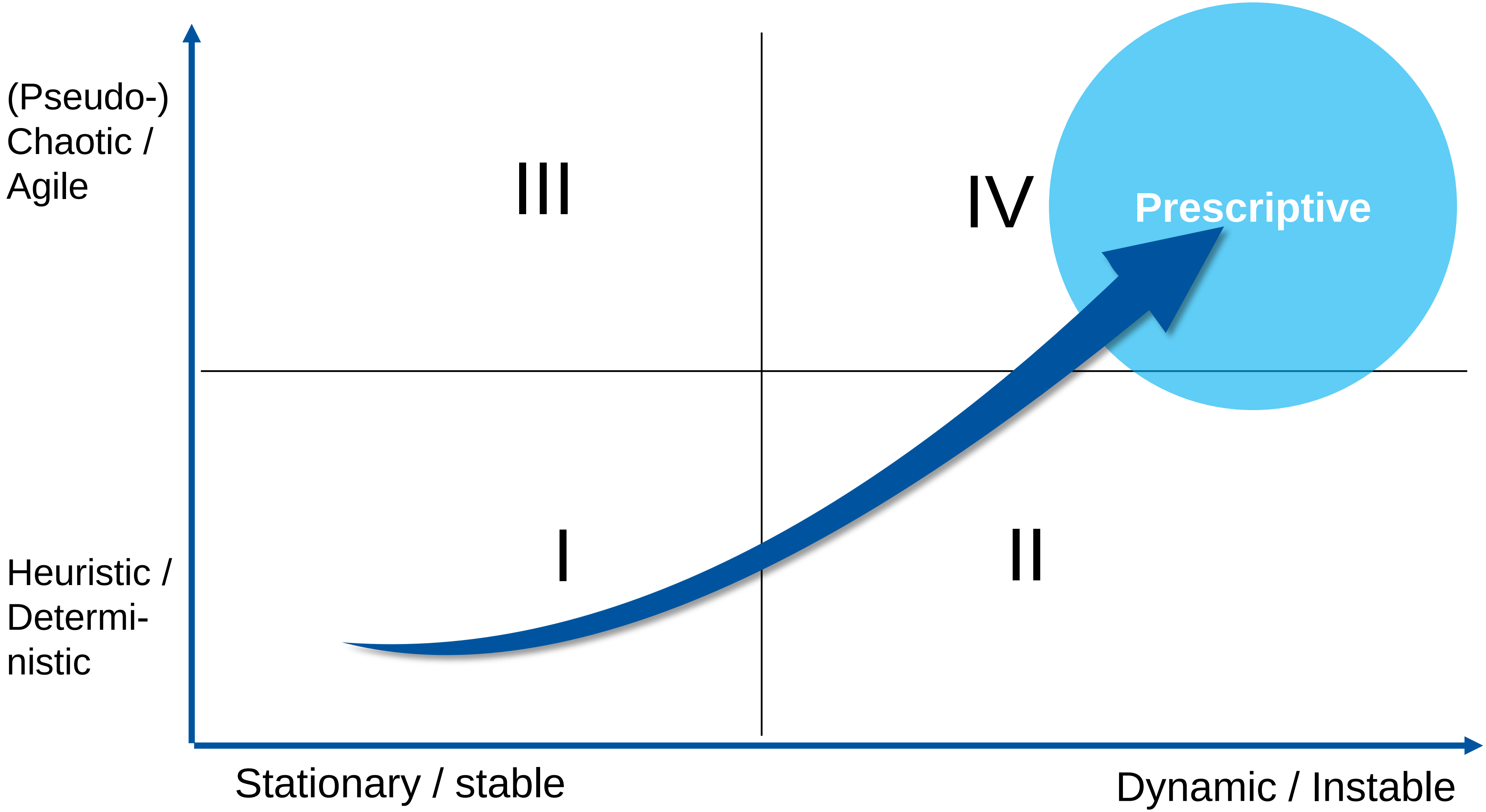
Stationary / stable

Dynamic / instable

Self-stabilizing control loops no longer match production needs



Self-stabilizing control loops no longer match production needs



Research Area #1:
Learning from Data with a-priori-Knowledge

Reference: Russel und Norvig 2010, D'Andrea 2013

Research Area #2: Learning from meshed Systems

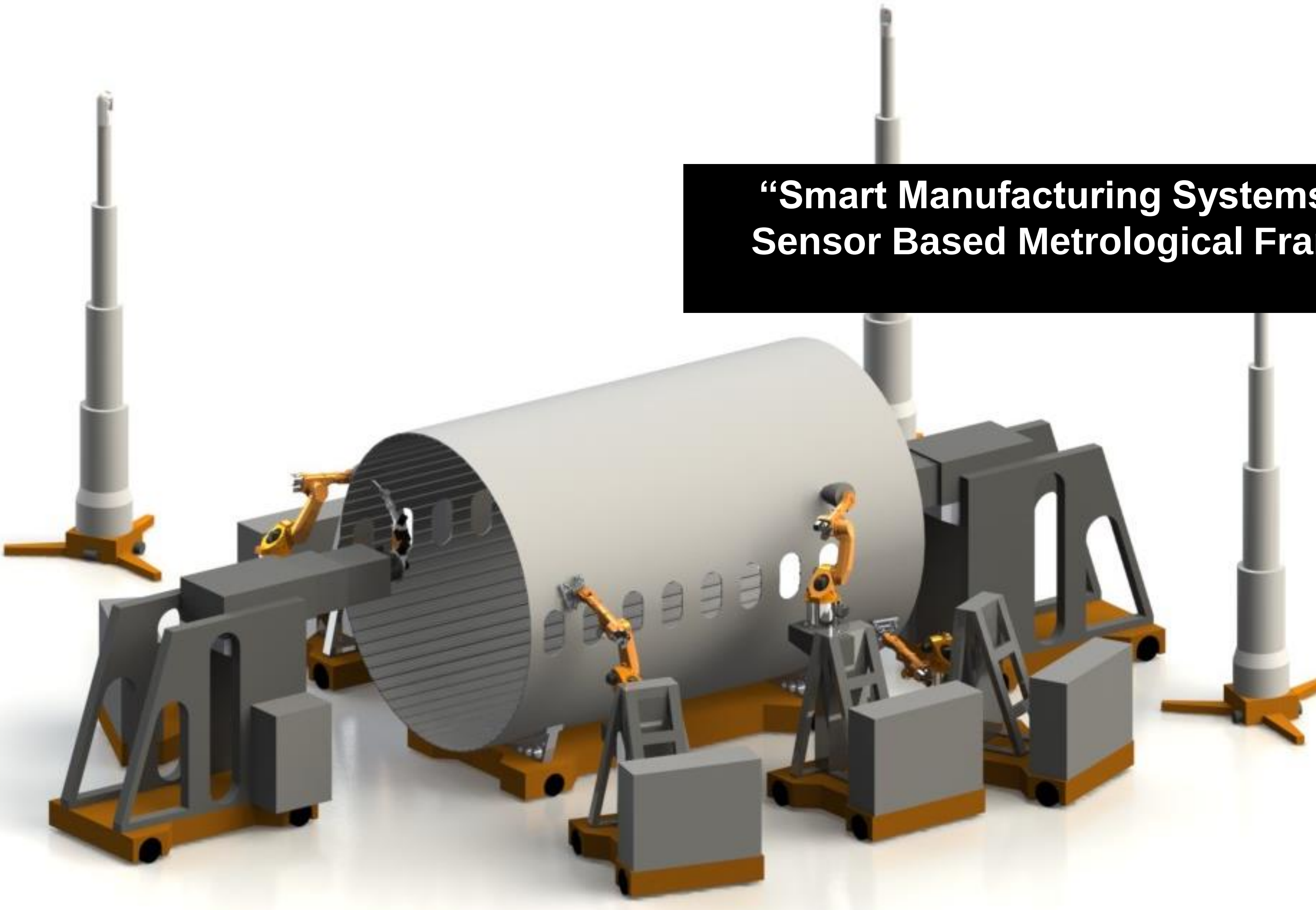
Reference: Levine (Google Research) 2016

Research Area #3:
Interaction with AI-Agents

Research Area #4:
Empowering people in socio-technical Systems

III – Multi Agent Assembly: Free Float, Flawless

“Smart Manufacturing Systems”: Sensor Based Metrological Frame



F3A: Free Float Flawless Assembly

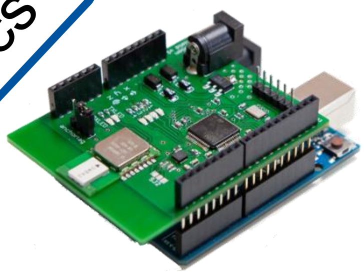
An Industry 4.0 Vision for Future Manufacturing Systems

- Transfer *and* machine-readable semantic description of machine-data (control, measurements, parameters) using OPC-UA
- Wireless RT communication with varying data rates (actual robot pose via LaserTracker) to GB/s for computer vision based quality inspection
- Model-based process control
  - Descriptive: Global Reference System to acquire current system state
  - Diagnostic: global process model to track and control
  - Predictive: Modelling mechanic part behavior
  - Prescriptive: Process control to achieve quality goals

Global Reference Systems as a Ressource

Measurement Uncertainty

Logistics



Navigation

Assembly

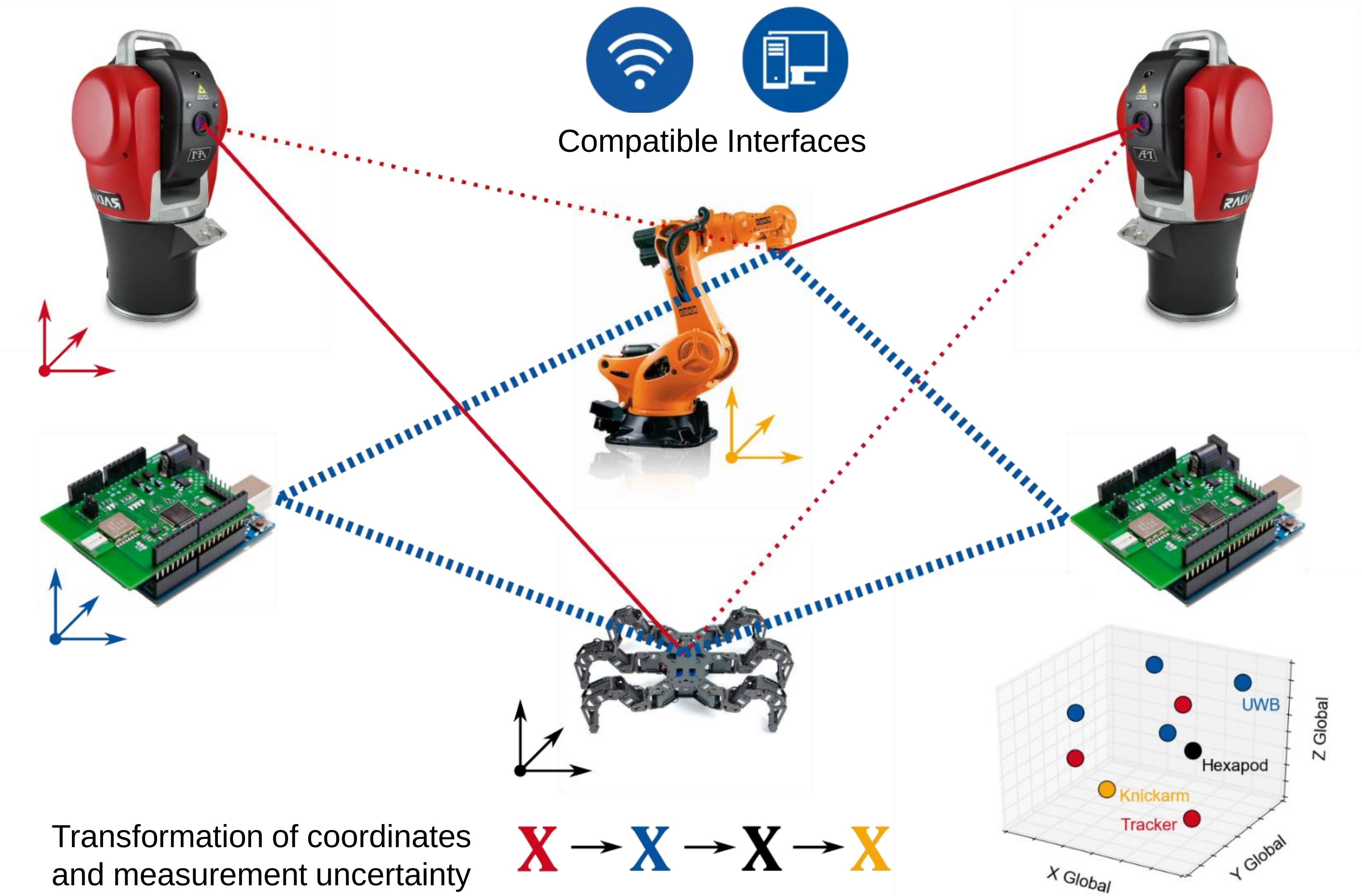
Inspection

Cost & Availability

Fraunhofer IPT

WZL | RWTH AACHEN UNIVERSITY

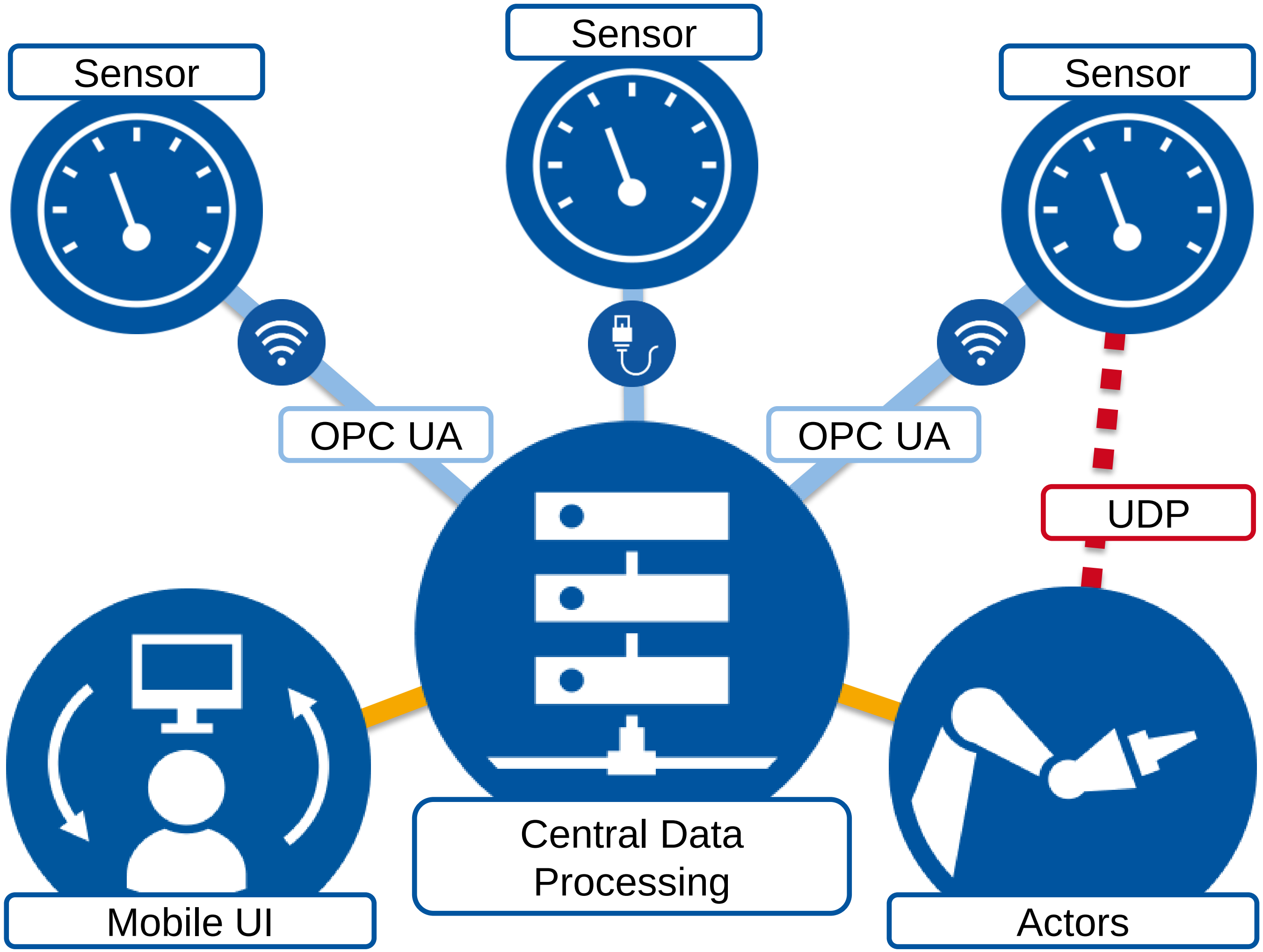
Multi-Sensor Metrology Environment



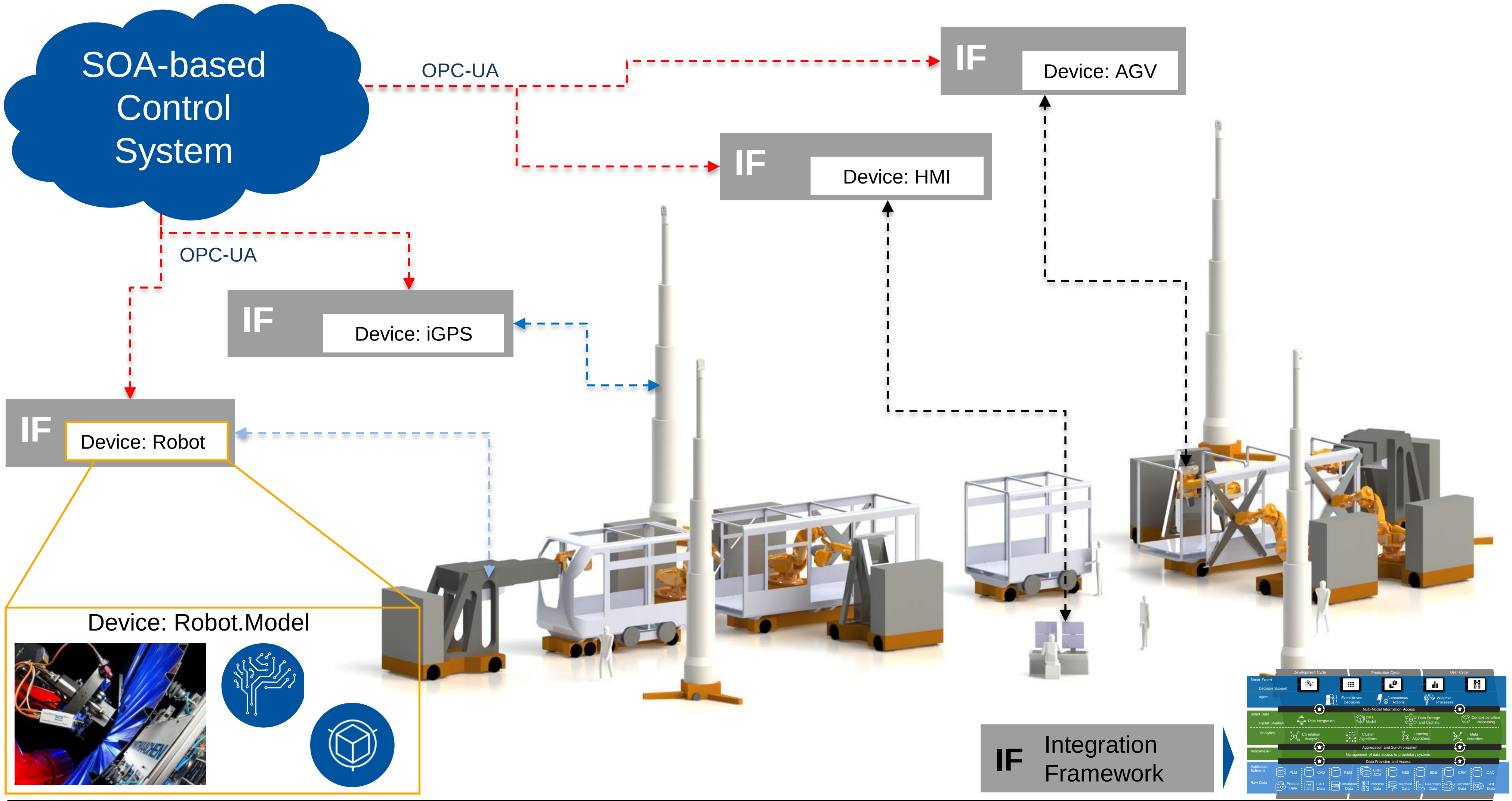
Transformation of coordinates
and measurement uncertainty

X → X → X → X

Communication Architecture



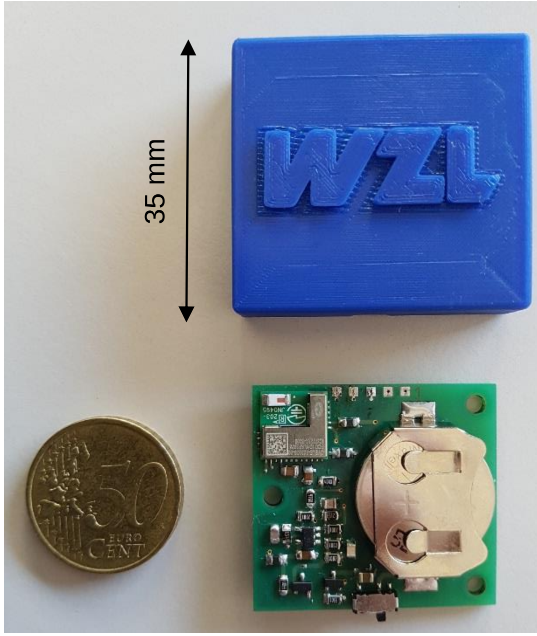
Integration Frameworks Connect All Relevant Entities to a Central Control System and Allocate Resources Using OPC-UA

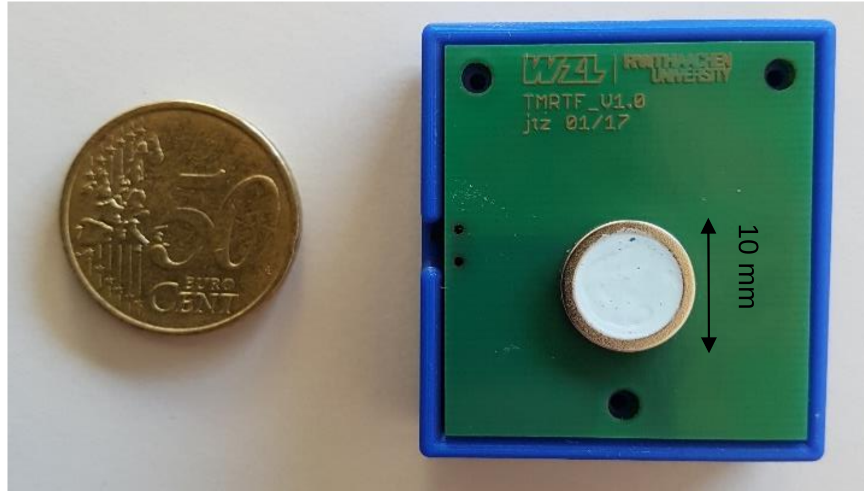


Virtual Metrology Frame – Demo App @ WZL Lab

Side Track:

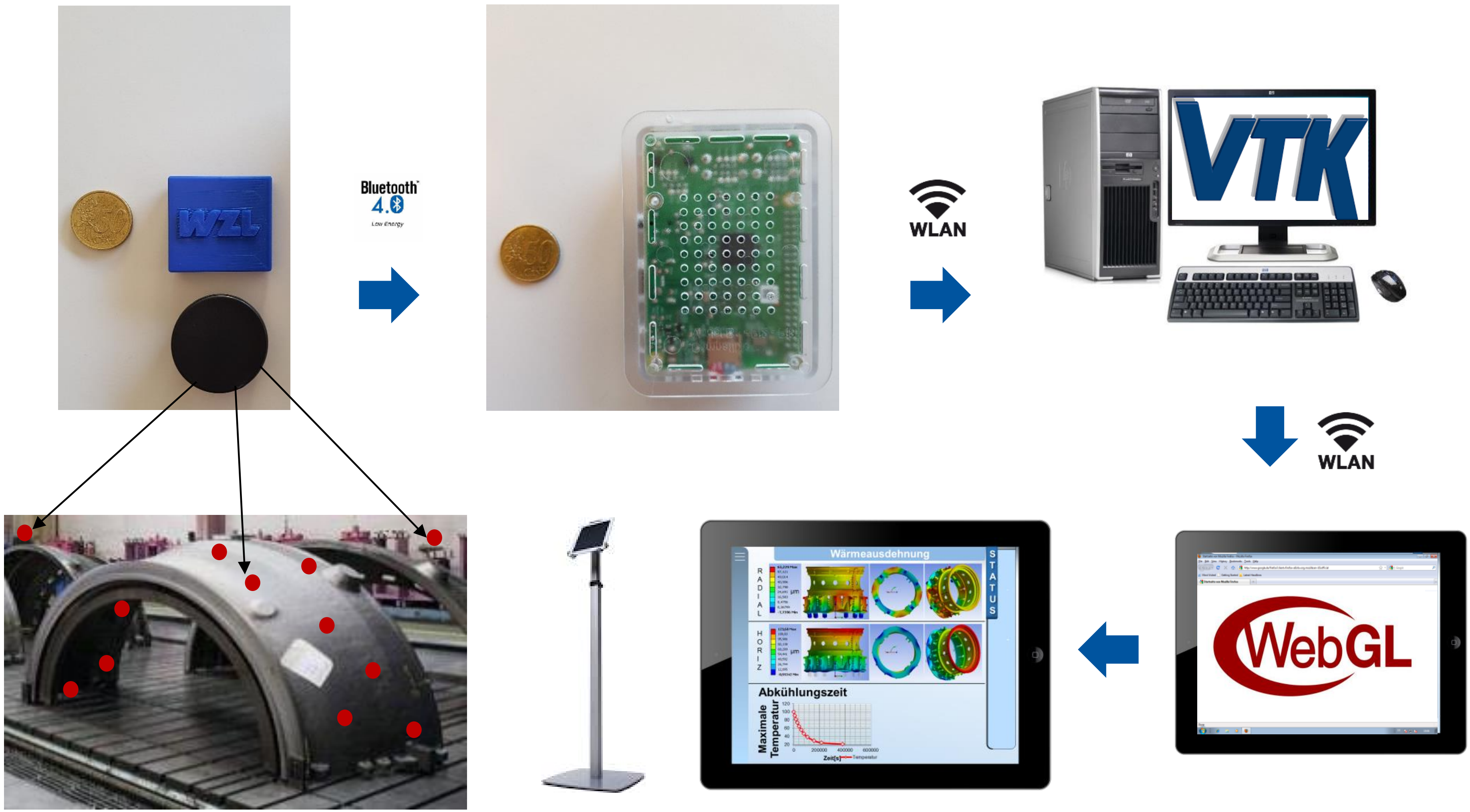
Global Reference not limited to Coordinates - Temperature





- Wireless, magnetic Pt1000 Thermistors
- Transmission via Bluetooth 4.1
- Variable update rate
- 3D-printed housing
- Transmission range of 15 m
- Resolution of 20 mK
- 1 year battery lifetime @ 60Hz update rate
- Water-proof, 0 °C to 80 °C operating range
- Temperature data available via web-interface

Side Track:
3-D Live-Calculation of thermoelastic State



Unknown measurement uncertainties in production environments

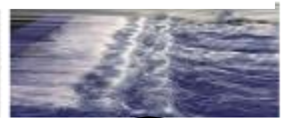
Thermo-elastic monitoring of workpiece

Problem

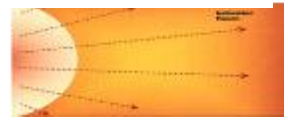
Unknown temperature- &
deformation condition espc.
Large workpieces

Ambient temperature

Airflow



Radiation



Coordinate meas. machine · *Measuring arm* · *Laser radar* · *Laser tracker* · *On-Machine-Measurement*

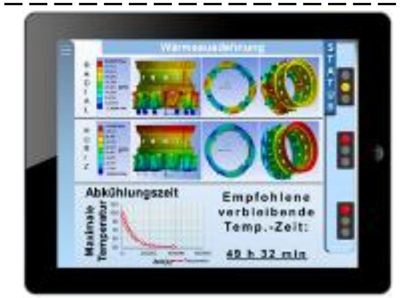
ZEISS CenterMax · *Faro GAGE* · *NIKON MV 350* · *FARO Vantage* · *GEORG ultraGrind*

Solution

Sensor- and model-based
temperature monitoring
for determination of deformation

Temp.-Datalogger

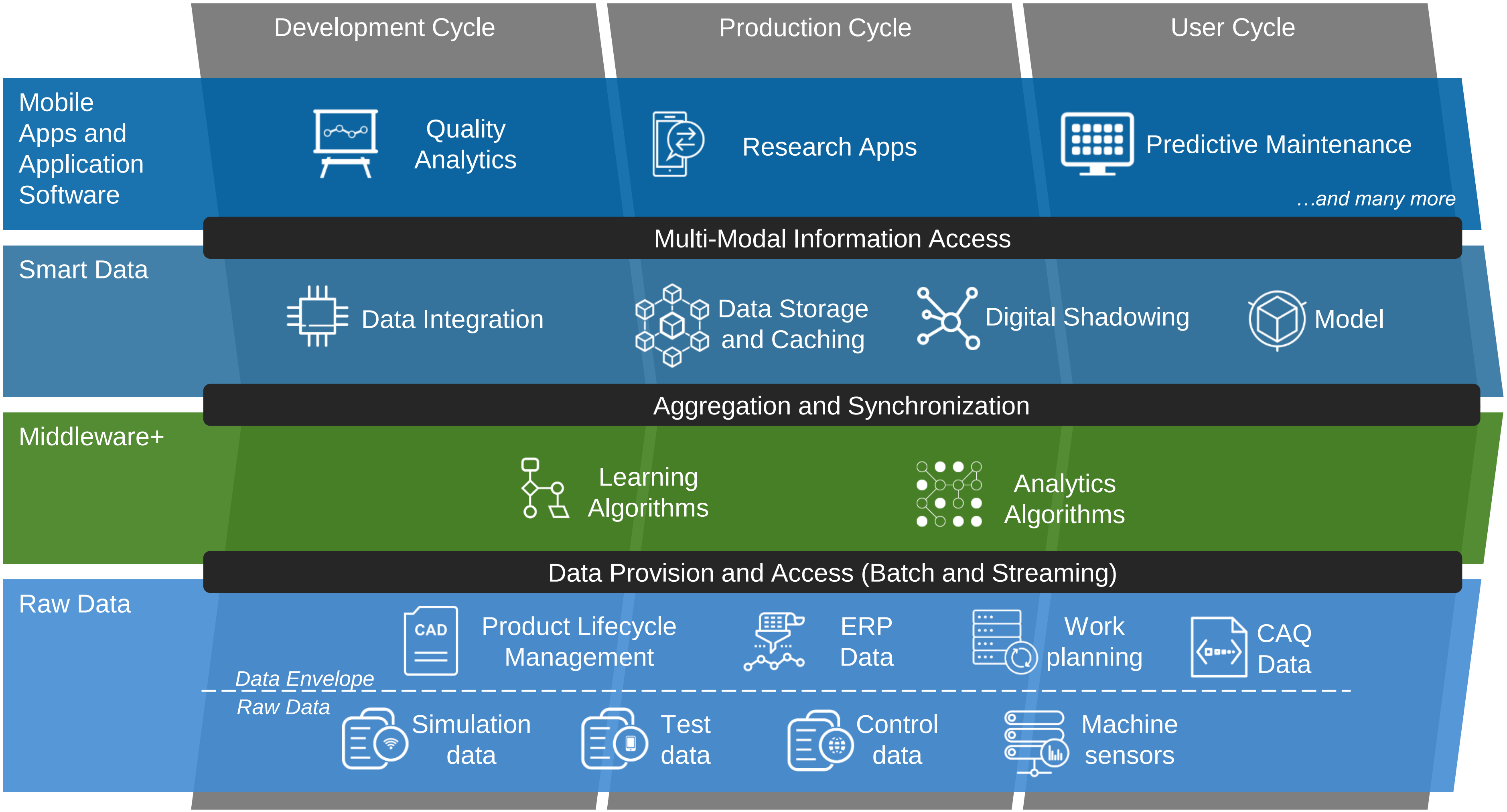
Ambient and surface temperature



Recommend minimum tempering time

Time dependant temperature distribution and expected measurement uncertainty for valid measurement results

Big Picture: Data Processing for Agile Enterprises



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Through Innovation in Consumer-Electronics,
Data is for free,
Information is precious.

I

Against the background of shorter product life cycles and increasing product complexity production engineering will depend on "more" and "better" understanding

II

Getting more information for agile demands from sophisticated methods for data analytics, dynamic models

III

“Smart expert” centered socio-technical systems reduce unwanted human induced errors, fault, flaws by “Tangible Metrology”

Conclusion:

For tomorrow’s production, the ‘Digital Shadow’ sets a new paradigm in science, for both profound understanding and better estimation in an agile environment.

Casting the case-adjusted ‘Digital Shadow’ from the ‘Digital Twin’ will be a metrological task

Thank You!

Thank You!

Dankjewel

谢谢

Grazie

Gràcies

Köszönöm

Thank you

Vielen Dank

Eskerrik asko

Спасибо

많은 감사

Obrigado

Muchas gracias

Gratias ago

شكراً

Merci

ありがとう

Ευχαριστώ

Prof. Dr.-Ing. Robert H. Schmitt

Chair of Metrology and Quality Management
Laboratory for Machine Tools and Production Engineering WZL | RWTH Aachen University