The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

ComTraForce

Force Sensors Digital Twin Concept and Reality

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24th of February 2023

www.cranfield.ac.uk

Cranfield Manufacturing

Precision Engineering

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

Surface Engineering and Precision Centre

The ultraprecision laboratory houses a range of advanced manufacturing technologies, such as:

- ultra-precision diamond turning, micro-milling and plasma figuring; and
- a comprehensive range of metrology instruments able to quality fabrication from nanometre to metre.

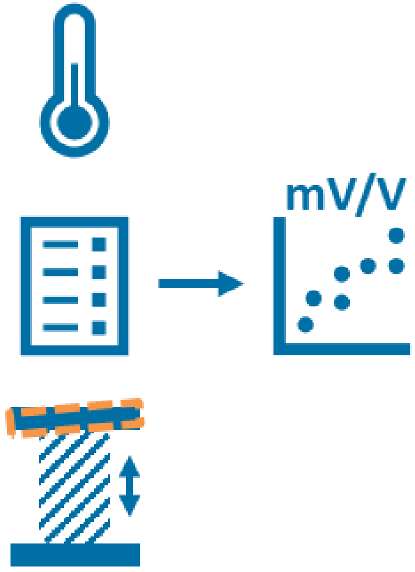
Our main precision facilities are thermally controlled to assure parts-per-million manufacturing accuracy.

Overview

Developing digital twins of force measuring devices in order to:

- Quantify effect of temperature, sensitivity stability, parasitic force component, etc. on the measurement uncertainty

- Investigate of the instantaneous response of the material behaviour of the load cell’s beam and the corresponding changes in the readings recorded by the sensors.



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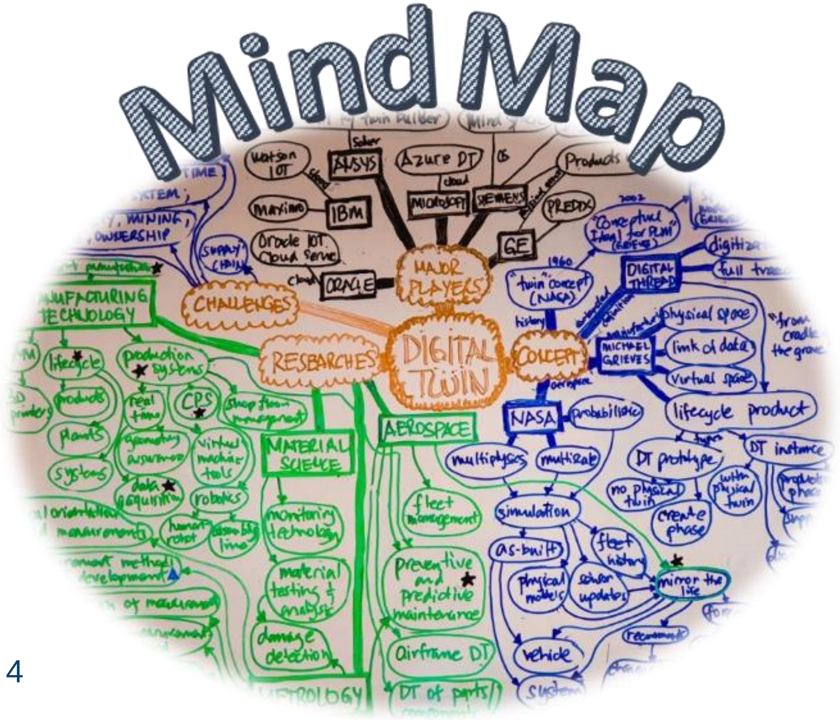
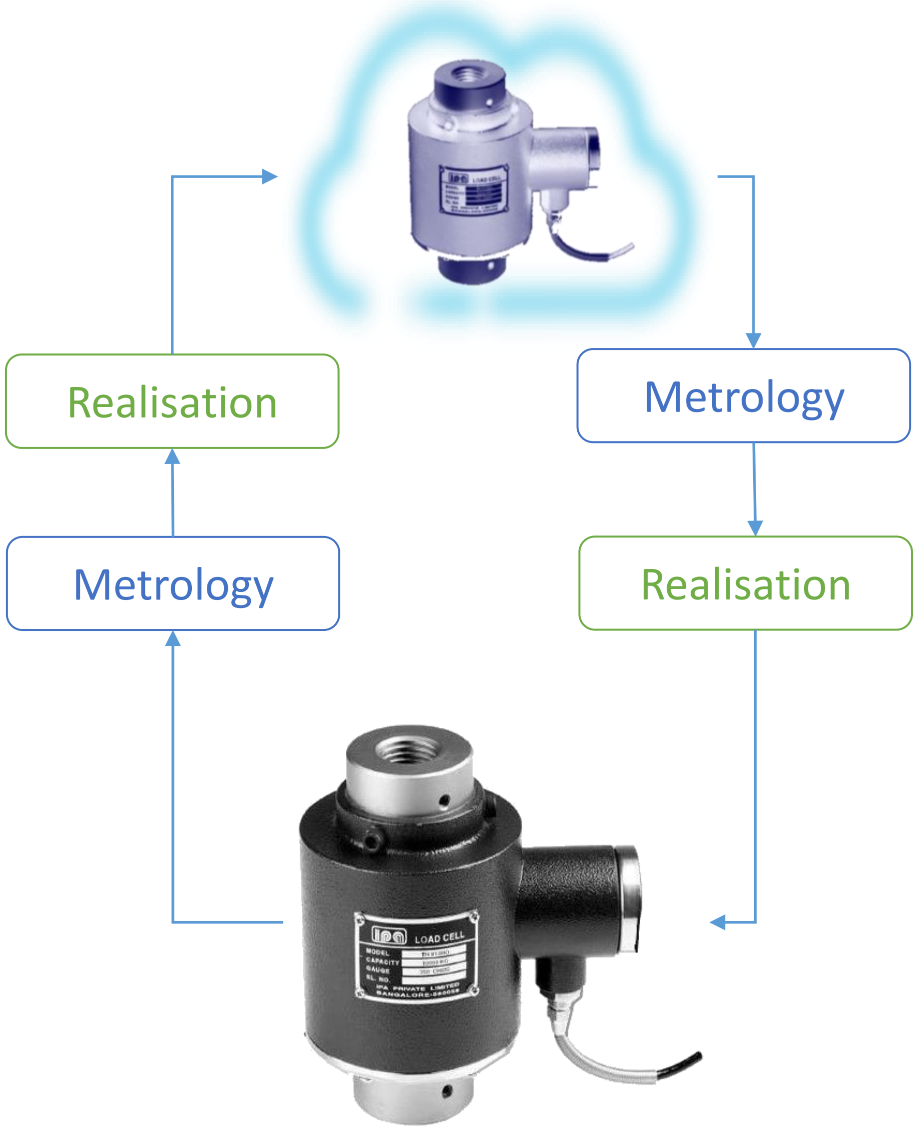
Digital Twin paradigm

Develop a secure online system that assures traceability of the information at all levels.

Enabling real-time exchange of information between the physical and virtual asset.



DT Journey



Safe use

Use the existing knowledge to predict the effect of creep

Creep effect depends on:

- Microstructure
- Time
- Temperature
- Stress

Engineering use of steady creep rate ($\dot{\varepsilon}_{cr}$):

For metals

stress dependence of the strain rate

creep activation energy

$$\dot{\varepsilon}_{cr} = K\sigma^n e^{\left(\frac{-Q_c}{RT}\right)}$$

constant

absolute temperature

stress

universal gas constant

(Bowman, 2004)

For polymers

constant

Larson-Miller Parameter

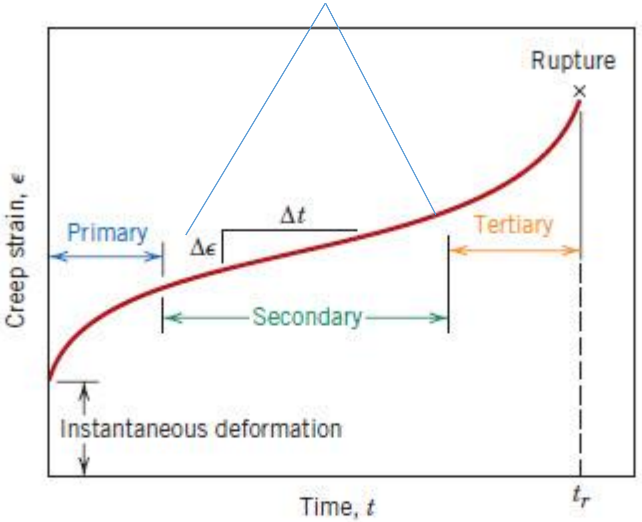
$$\dot{\varepsilon}_{cr} = 10^{C - \frac{LMP}{T}}$$

(Li and Dasgupta, 1993)

Estimated from experiments

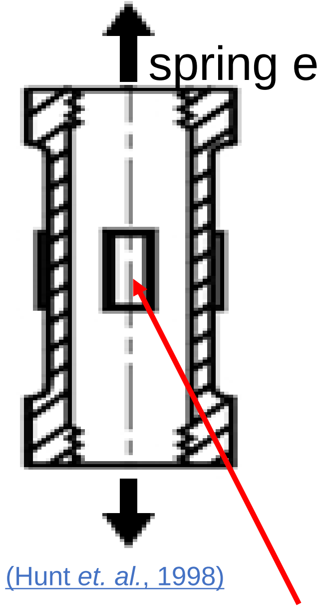
Region of safe operation

(Sato, Omote and Sato, 2014).



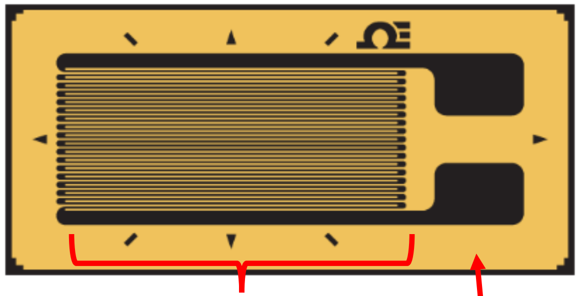
(Total Materia, 2010)

Assumptions



(Hunt *et. al.*, 1998)

strain gauge



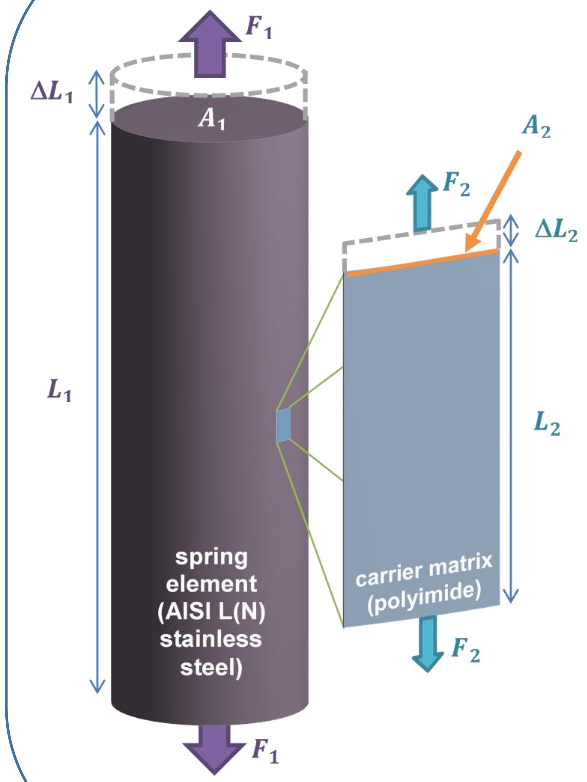
metal foil pattern (measuring grid)

carrier matrix

(Omega UK, 2019)

Digital Twin

Assumptions
DATA



Spring Element AISI 316 L(N)	
Height	140 mm
Diameter	43 mm
Young's Mod.	190 GPa
Carrier Matrix Polyimide	
Height	7.5 mm
Width	4.6 mm
Thickness	30 µm
Young's Mod.	2.5 GPa
Yield Point	69 MPa

PHYSICAL LOAD CELL

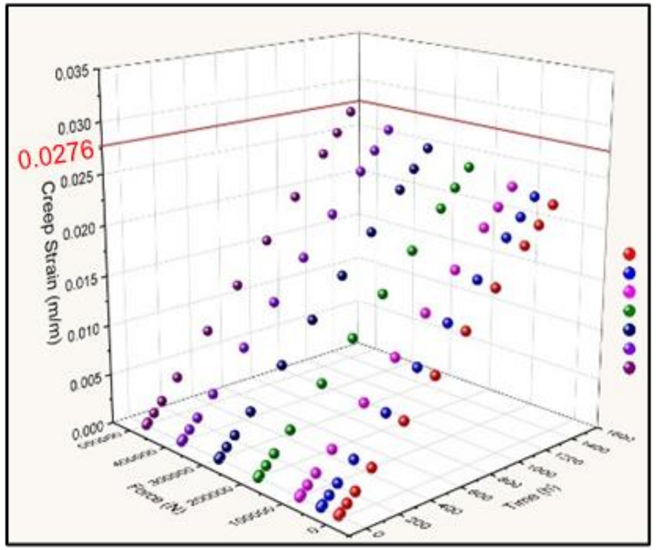
F

T

Numerical Model

Digital Constructs

DECISION
The red line defines the boundary at which the creep strain must not be exceed!



Metrological use

A measurement model based approach

- Sensor output will be described by a probability distribution function, often assumed $N(\mu, \sigma)$.

Two basic questions:

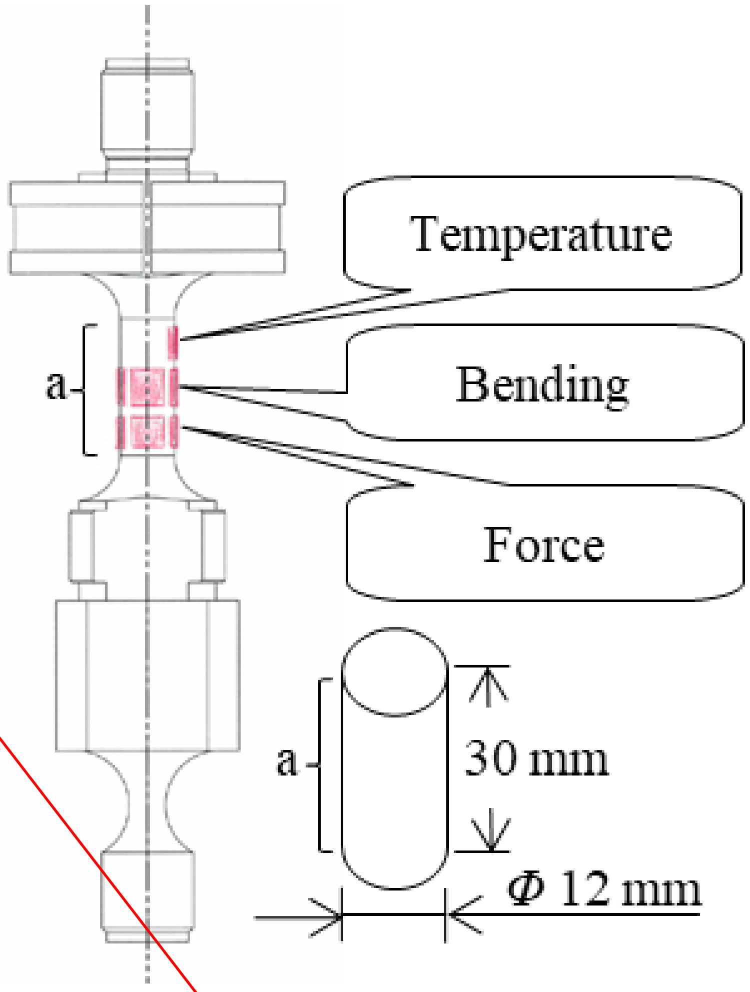
- **What is the measurement model and the required accuracy?**
- **How fast the physical and virtual asset need to exchange information?**

Analytical Solution
in mV/V

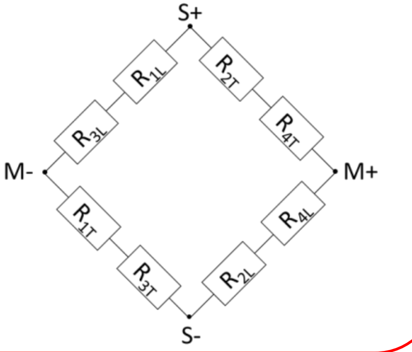
$$I = 1000 \times \frac{k\varepsilon(1+\upsilon)}{2 + k\varepsilon(1-\upsilon)}$$

$$\varepsilon = \frac{4F}{E\pi d^2}$$

Inputs:
Force, Young modulus,
Poison ratio,
Dynamometer diameter.



Source of
non-linearity.
Bridge exclusive!



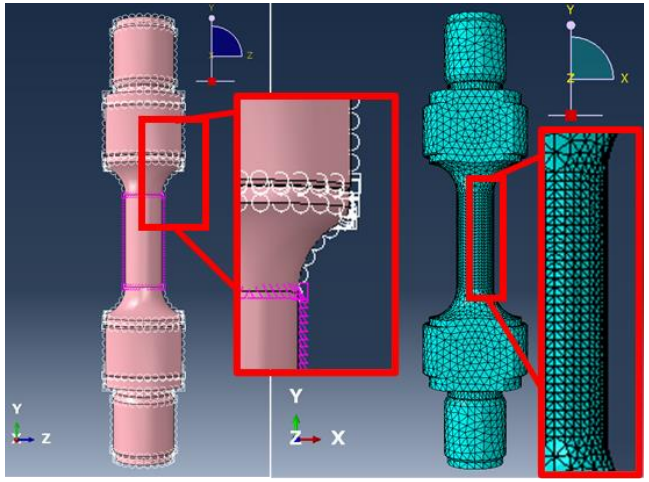
FEA static model

Can
Monitor trends
Be used for complex shape dynamometers.

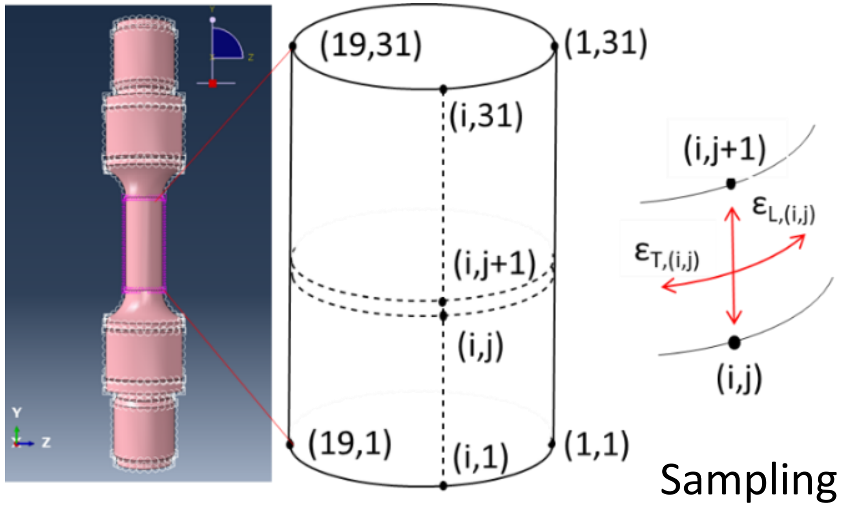
Cannot
Be fast
Be used without calibration

FEA modelling of static calibration.

- Traceability NMI – **20 ppm** RDG
- Bridge expected to introduce a linearity error of approximately **20 ppm** FS.
- FEA require meshing, sampling and constraints. All introduce modelling errors:
    - Meshing difference - **35 ppm** RDG
    - Applied force conditions – over **100 ppm** FS
    - Sensors bonding – over **200 ppm** RDG
- Most of FEA errors appear as a bias (can be corrected by calibration)



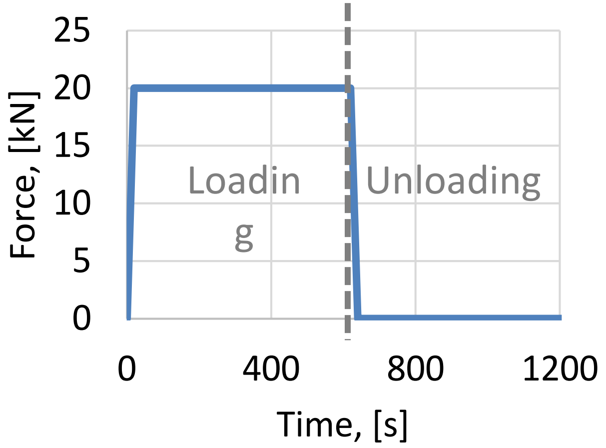
Meshing example



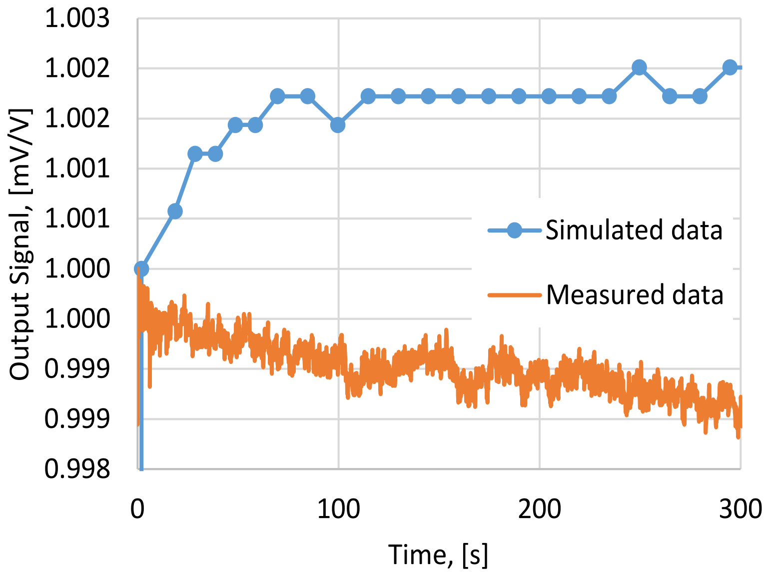
Sampling example

Continuous calibration test model

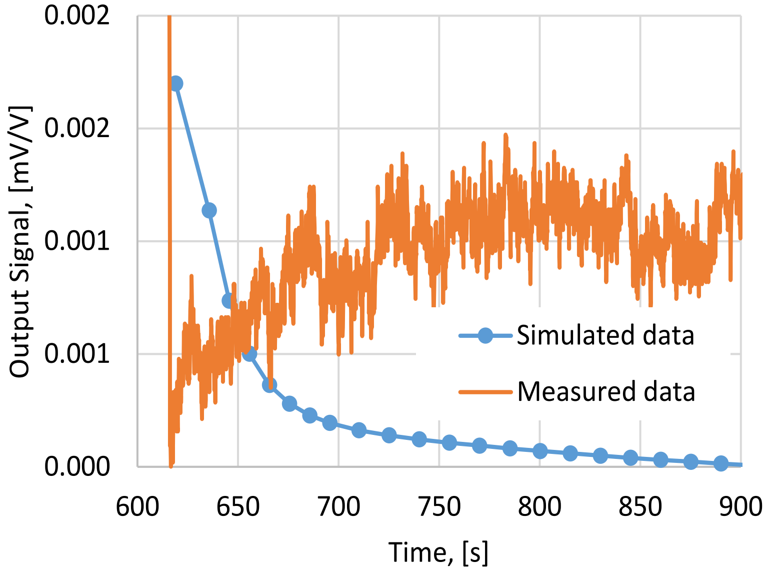
- Creep test performed at the end of the static procedure.
- Transducer is loaded at full scale and held for five minutes.



Force vs time profile for continuous test



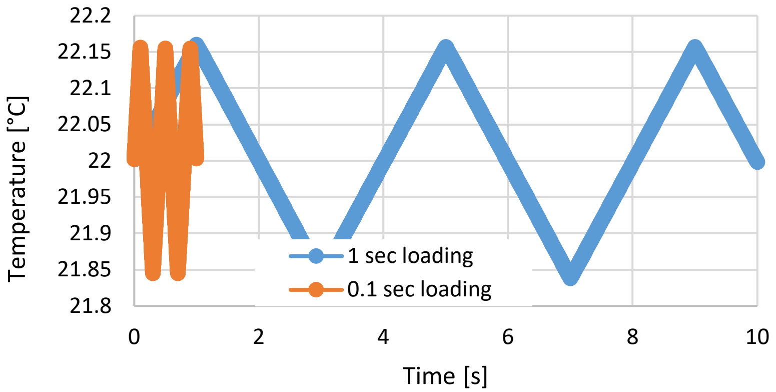
Comparison between the simulated and the measured data during **loading** stage



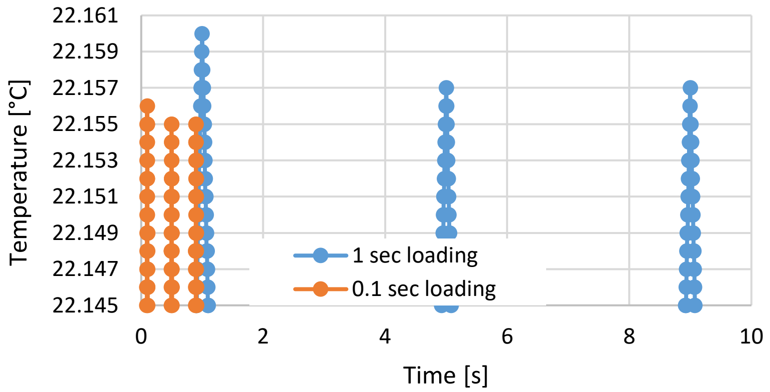
Comparison between the simulated and the measured data during **unloading** stage

- The simulated and measured data show opposite trends.
- The measured data represents the strain gauge output signal and the simulated one the output of the load cell.
- Experiments (Kühnel 2013) showed that creep recovery of the load cell acts in opposite direction to creep of the strain gauge and the glue layer.

Dynamic calibration test model



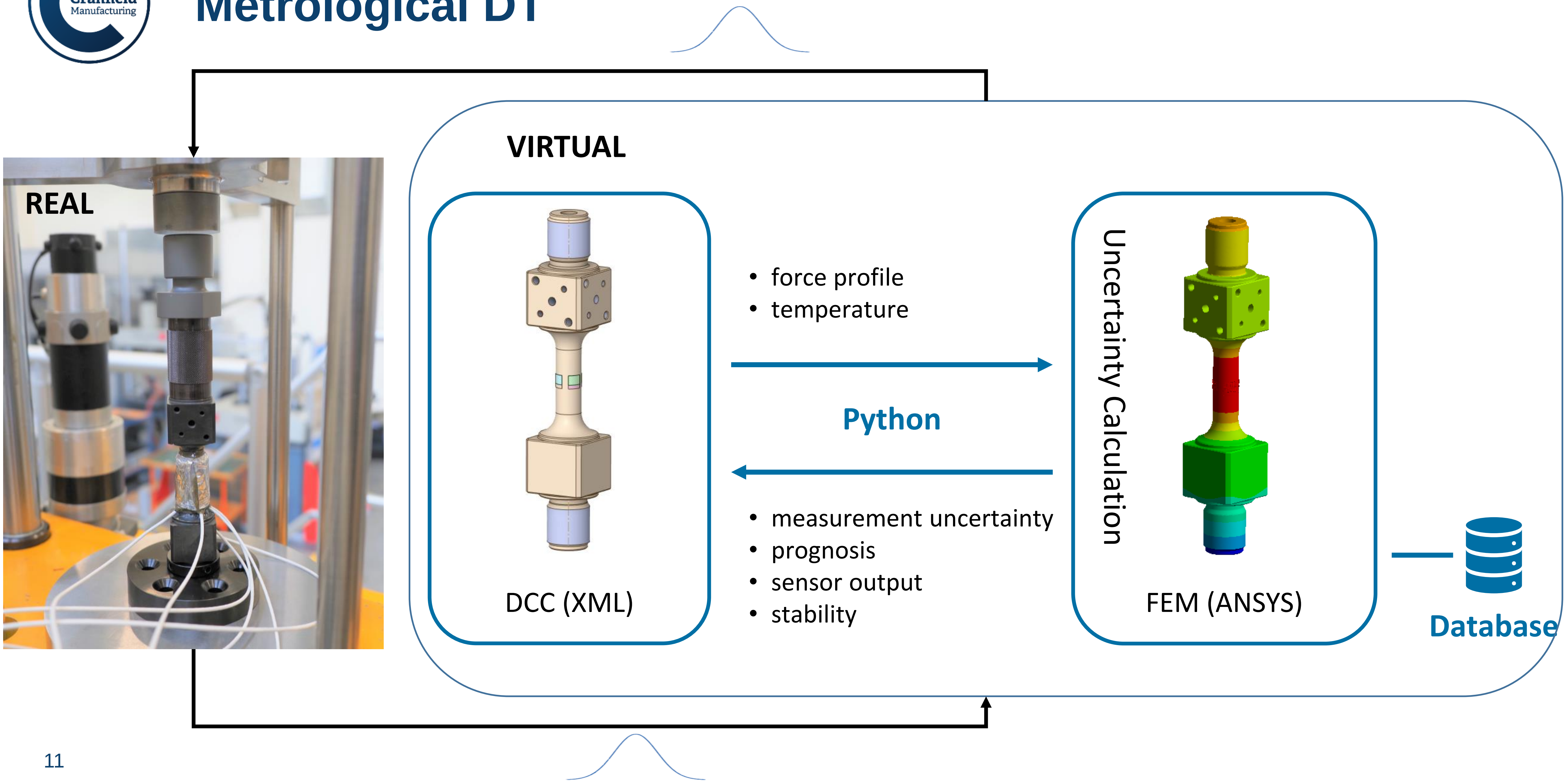
Simulated temperature profile during dynamic calibration process, full range view



Simulated temperature profile during dynamic calibration process, high temperature resolution view

- Axial load was applied with two loading rates of 0.1 and 1 sec
- Three loading cycles were simulated in order to maintain a reasonable simulation time
- The profiles for both loading rates show a slight decrease of the temperature peaks for the second and third cycles.
- The fluctuation of the temperature due to thermoelastic effect during cyclic loading is of about 0.15 °C.
- It agrees well with the cyclic test on AISI 1045 mild steel cylindrical specimens (Lee, H. T. & al. 1993).

Metrological DT



Conclusions and future work

- FEM models output can be used to evaluate the input PDFs in GUM S1 Monte Carlo approach for:
    - non-compliant loading and unloading,
    - relaxation effect from the thermomechanical beam behaviour.

- Dynamic simulations are computationally demanding.
    - Surrogate models should be developed and validated by FEA.

- Future work could look into different modelling strategies which can assess the strain gauge real behaviour.

- Current and past experimental studies can be used by AI to predict the strain gauges creep behaviour.

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Thank you!

Contributors

- PTB
- INRIM
- USTUTT
- CEM

EMPIR EURAMET

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States