EPM-FunSNM: from Generic Tools to Real-World Applications

FORUM-MD Workshop on Metrology for Complex Sensor Networks

Shahin Tabandeh

10/02/2025 VTT – beyond the obvious

Introduction

"The FunSNM project offers strong metrological support to the digital transformation by not only addressing the reliability of sensor networks but also ensuring innovation, practicality, and contribution to standards, making it a robust and comprehensive initiative in advancing sensor network metrology"

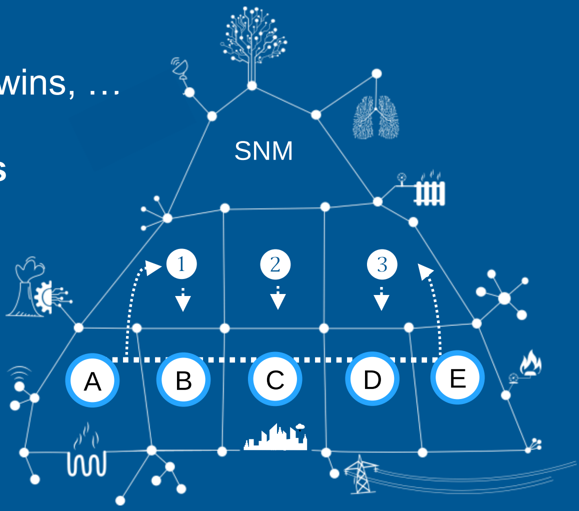
FunSNM structure

① Uncertainty and data quality methods for sensor networks
- Generic methods for uncertainty propagation
- Data Quality Metrics
- Traceability: self- and co-calibration, uncertainty-aware sensor fusion, digital twins, …

② Methods for the metrological assessment of distributed sensor networks
- Characterization aspects of distributed sensor network for assessment
- Infrastructure requirements of the distributed sensor network
- Risk analysis of distributed sensor networks

③ Software frameworks and semantics for large transient sensor networks
- Automated application of methods for uncertainty evaluation and data fusion
- Automated integration of metrological and data quality information
- Machine-interpretable description and semantics

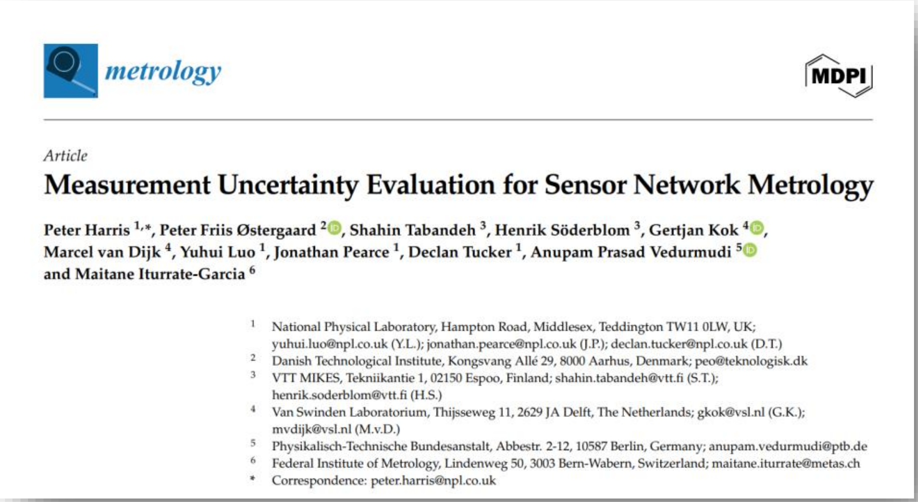
④ Use case demonstrations and feedback (A - E)



Generic tools for SNM

Generic tools for uncertainty estimation

- Model-based Tree Structured Mesh Networks
- Laplace Domain Tools for Co-Calibration of Sensors in a Network
- Accounting for Correlation in the Measurements Made by the Sensors in a Network
- Drift Estimation for the Sensors in a Network


metrology MDPI

Article

Measurement Uncertainty Evaluation for Sensor Network Metrology

Peter Harris [1,*], Peter Friis Østergaard [2], Shahin Tabandeh [3], Henrik Söderblom [3], Gertjan Kok [4], Marcel van Dijk [4], Yuhui Luo [1], Jonathan Pearce [1], Declan Tucker [1], Anupam Prasad Vedurmudi [5] and Maitane Iturrate-Garcia [6]

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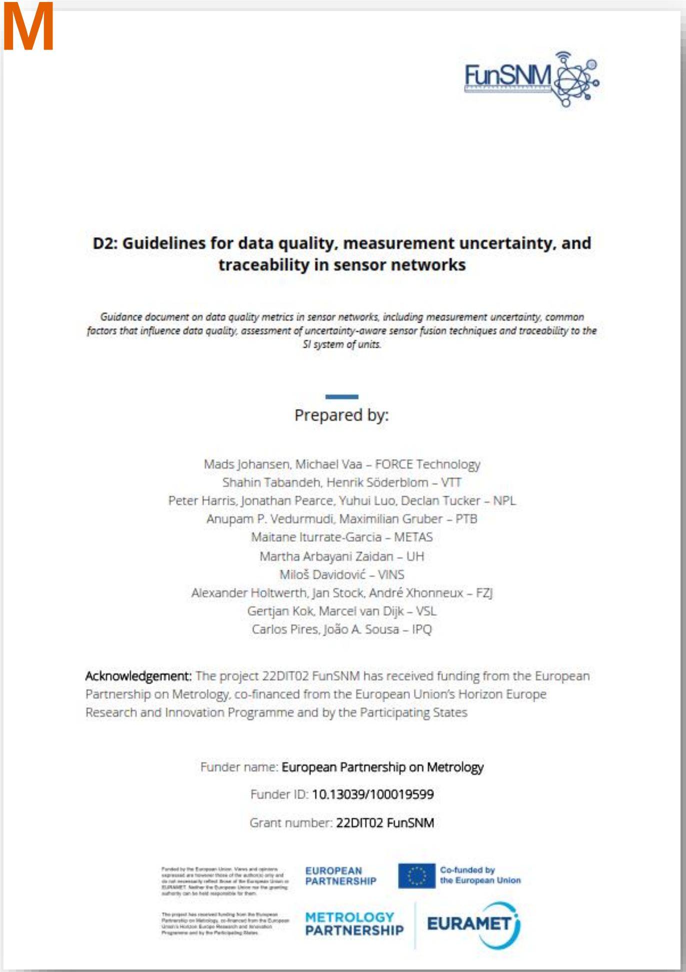
Generic tools for SNM

Data Quality

- Data quality metrics for sensor networks
- Data requirements in a sensor network
- Data quality and validation methods

Metrological traceability

- Methods for In-situ Self-calibration or co-calibration with reference sensors
- Methods for Uncertainty-aware Sensor Fusion
- Digital twins and digital shadows



D2: Guidelines for data quality, measurement uncertainty, and traceability in sensor networks

Guidance document on data quality metrics in sensor networks, including measurement uncertainty, common factors that influence data quality, assessment of uncertainty-aware sensor fusion techniques and traceability to the SI system of units.

Prepared by:

Mads Johansen, Michael Vaa – FORCE Technology
Shahin Tabandeh, Henrik Söderblom – VTT
Peter Harris, Jonathan Pearce, Yuhui Luo, Declan Tucker – NPL
Anupam P. Vedurmudi, Maximilian Gruber – PTB
Maitane Iturrate-Garcia – METAS
Martha Arbayani Zaidan – UH
Miloš Davidović – VINS
Alexander Holtwerth, Jan Stock, André Xhonneux – FZJ
Gertjan Kok, Marcel van Dijk – VSL
Carlos Pires, João A. Sousa – IPQ

Acknowledgement: The project 22DIT02 FunSNM has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States

Funder name: European Partnership on Metrology

Funder ID: 10.13039/100019599

Grant number: 22DIT02 FunSNM

Instituto Português da Qualidade

João A. Sousa
Carlos Pires
João Abrantes

Relevant papers and presentations:

João A. Sousa, Alistair B. Forbes; **Gaussian processes and sensor network calibration**; *Measurement: Sensors*; 2024 https://doi.org/10.1016/j.measen.2024.101512
Presentation at the IMEKO World Congress, August 2024

Limitations of conventional methods for uncertainty quantification
Report on **Best practices and processes in data quality metrics for typical use cases in the areas of district heating, gas flow and air quality measurements**
Assessment of data metrics of distributed sensor networks
Report on **Risk analysis related to sensor networks**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In Press, Corrected Proof   What's this?

Gaussian processes and sensor network calibration

João A. Sousa [a], Alistair B. Forbes [b]

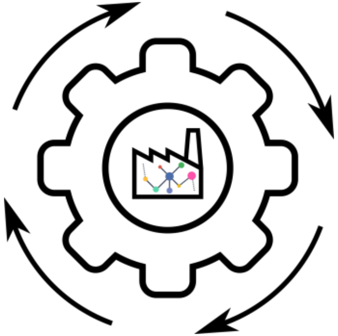
IPQ   NPL National Physical Laboratory

The main contribution of IPQ has been in the study of data quality metrics, uncertainty quantification and risk analysis   relevant for sensor networks

Software frameworks and semantics for sensor networks

Research highlights

- Demonstration of consensus based sensor networks using multi-agent systems
- Literature reviews and expert surveys:
  - Automation in sensor networks
  - Data quality in transient sensor networks
  - Explainable AI in sensor networks

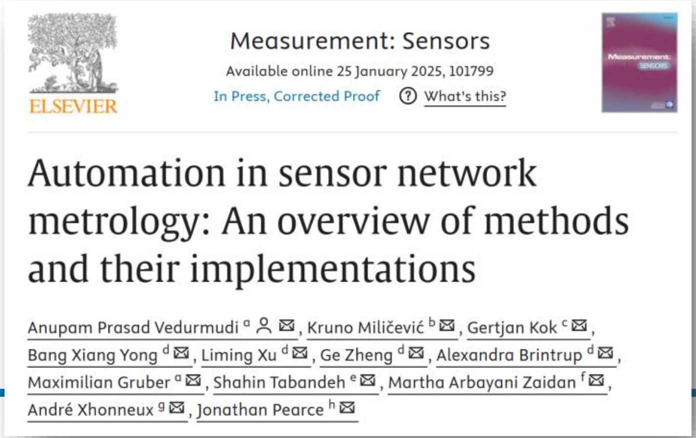


Researchers involved

Anupam Prasad Vedurmudi (PTB)
Kruno Miličević (RandomRed)
Bang Xiang Yong (UCAM)
Michael Vaa (FORCE Technology)
Mads Johansen (FORCE Technology)
João Alves e Sousa (IPQ)
Carlos Pires (IPQ)
Shahin Tabandeh (VTT)
Gertjan Kok (VSL)
Marcel van Dijk (VSL)
Martha Abayani Zaidan (UH)
Maximilian Gruber (PTB)
André Xhonneux (FZJ)
Jonathan Pearce (NPL)
Jean-Lauren Hippolyte (NPL)

Papers and presentations

- A. P. Vedurmudi “Automation in sensor network metrology: An overview of methods and their implementations,” Presentation, IMEKO 2024, Hamburg
- A. P. Vedurmudi et al., “Automation in sensor network metrology: An overview of methods and their implementations,” Measurement: Sensors, p. 101799, 2025, doi:https://doi.org/10.1016/j.measen.2024.101799.
- A. P. Vedurmudi, Quality of Data and Traceability for Soft Sensors, CIM 2025, Lyon (Upcoming)
- Github organization with project results: https://github.com/FunSNM



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Automation in sensor network metrology: An overview of methods and their implementations

Anupam Prasad Vedurmudi [a], Kruno Miličević [b], Gertjan Kok [c], Bang Xiang Yong [d], Liming Xu [d], Ge Zheng [d], Alexandra Brintrup [d], Maximilian Gruber [a], Shahin Tabandeh [e], Martha Arbayani Zaidan [f], André Xhonneux [g], Jonathan Pearce [h]

Uncertainty Propagation in Multi-dimensional reputation-weighted sensor network

Bang Xiang Yong, Alexandra Brintrup
University of Cambridge

UNIVERSITY OF CAMBRIDGE

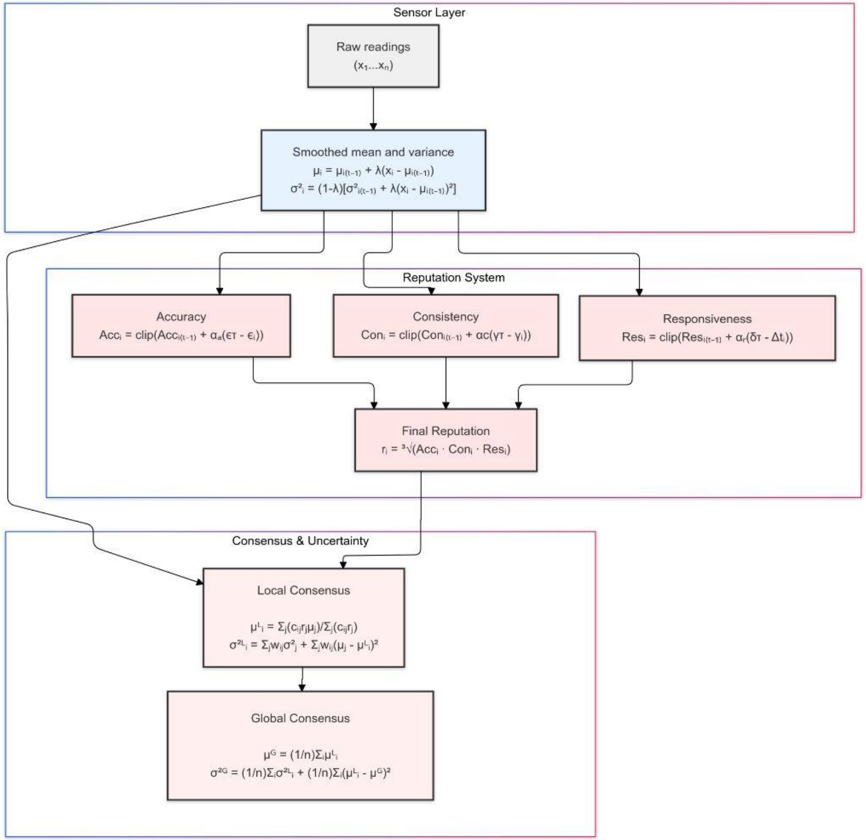
Key features:

1. Hierarchical uncertainty propagation

- Local level: Between nearby sensors
- Global level: Across entire network
- Weighted by reputation scores
- Law of total variance
  - decomposition into epistemic and aleatoric uncertainty

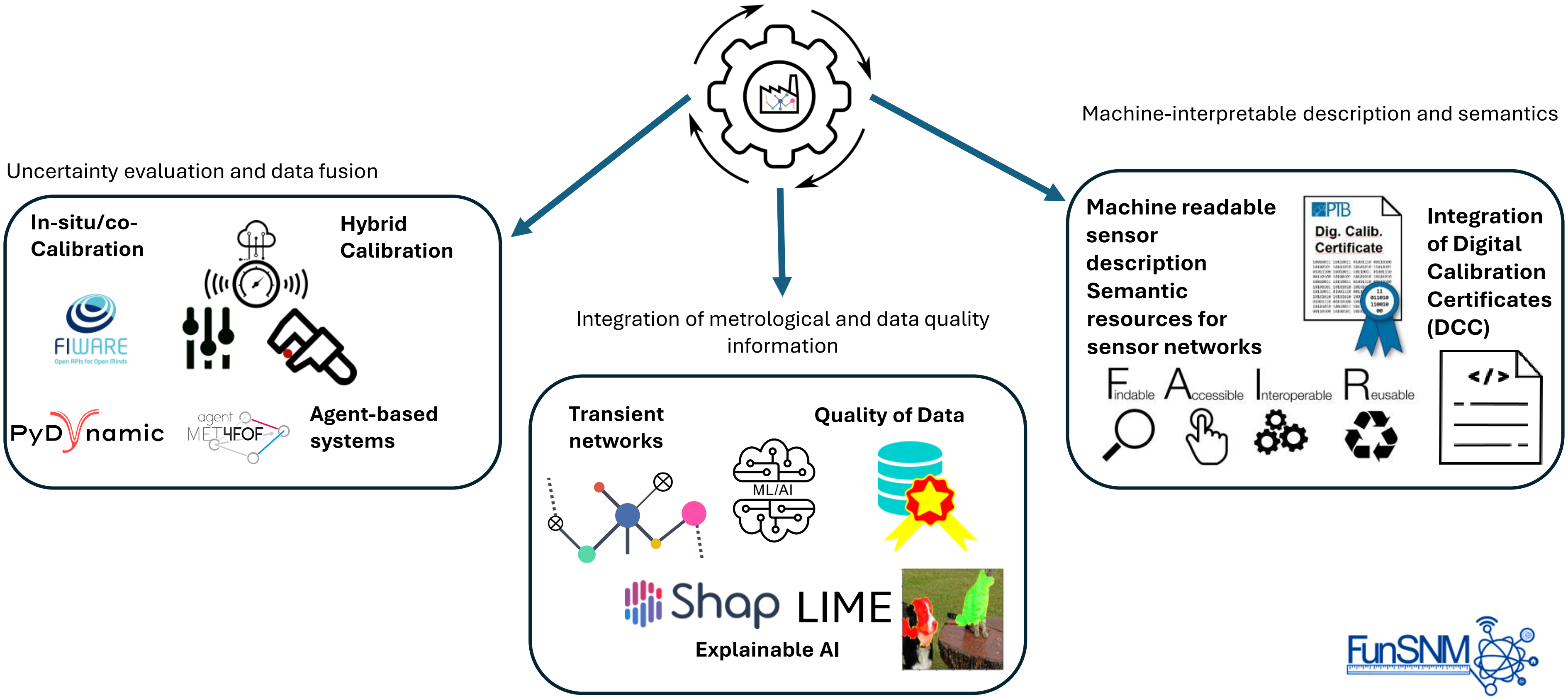
2. Multi-dimensional Reputation System

- Multi-dimensional scoring
- Automatically reduces influence of faulty sensors and increase influence of reliable sensors
- **i) Accuracy**: relative error with neighbours
- **ii) Consistency**: penalise sensors with higher coefficient of variation
- **iii) Responsiveness**: penalise outdated or irresponsive sensors



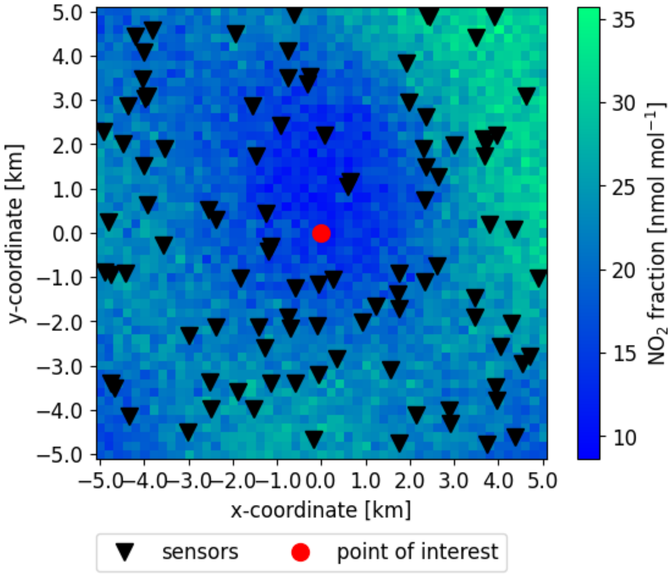
Framework illustrating data flow from sensors' raw readings, reputation system to forming consensus readings.

Software frameworks and semantics for sensor networks



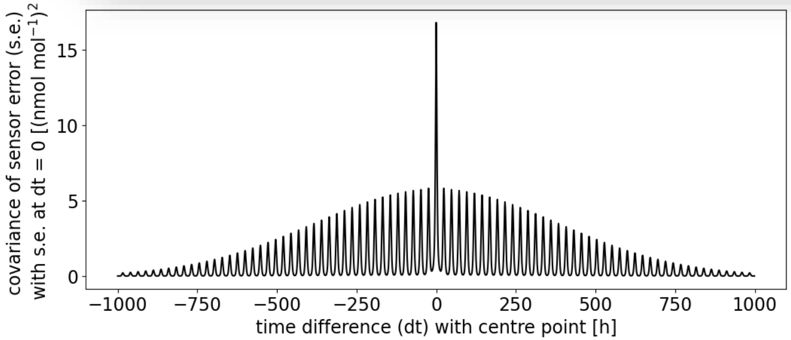
Correlated uncertainties in sensor networks

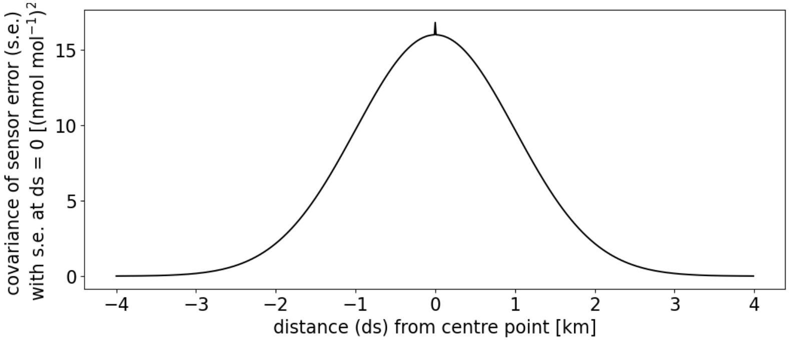
- Estimate and model temporal and spatial correlations in measurement errors of NO_2 sensors
  - Partially based on open-source dataset QUANT: https://catalogue.ceda.ac.uk/uuid/ae1df3ef736f4248927984b7aa079d2e/
- Study effect of (not) incorporating correlated sensor errors in Gaussian process model for sensor aggregation and interpolation tasks



Modelling and determining correlations in sensor networks

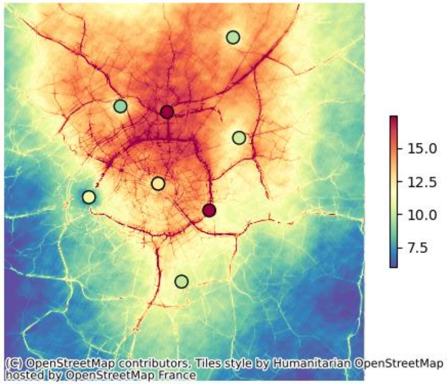
Gertjan Kok [a], Marcel van Dijk [a], Peter Harris [b], Anupam Vedurmudi [c]

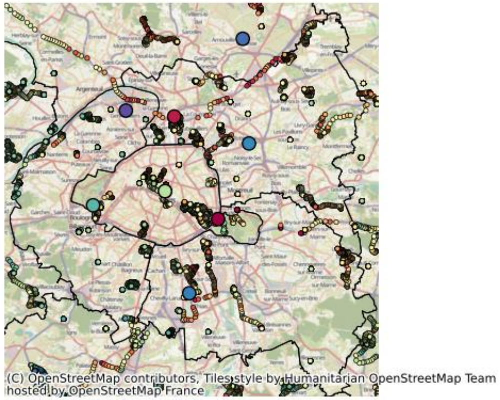




AIR QUALITY HIGH RESOLUTION MAPS IN PARIS

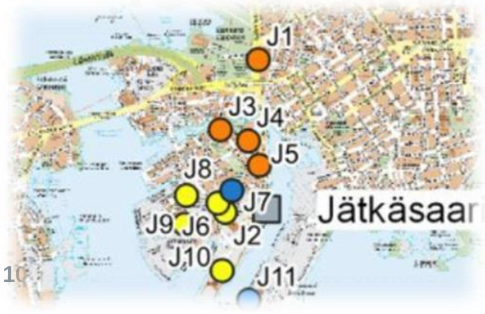
- Goal: produce High-Resolution maps of the amount-of-substance fraction of some pollutants (e.g., NO2 , PM10 , PM2,5…) using both measurements from reference stations and (possibly mobile) low-cost sensors
- Achievements so far:
  - Proposal of a scalable methodology that takes into account the different types of sensors
  - Uncertainty quantification of the sensors used by Airparif
- A joint effort by Nicolas Fischer, Tatiana Macé, and Sébastien Petit from LNE and Christophe Debert and Adrian Arfire from Airparif

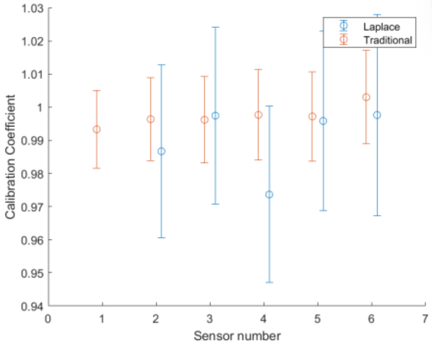


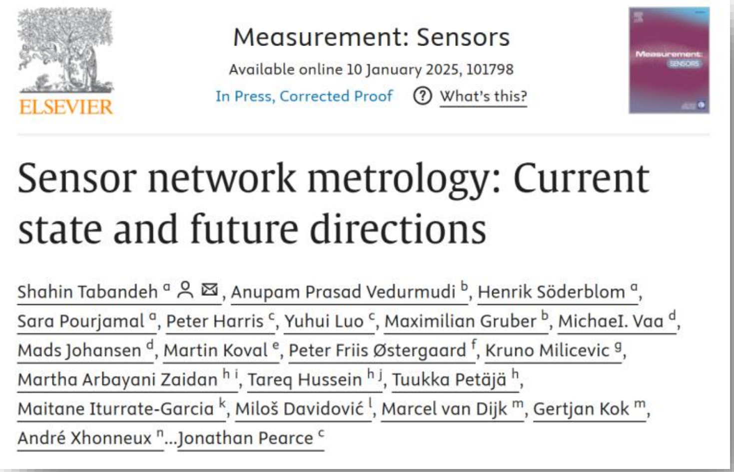


Laplace-domain tools for sensor networks

- Laplace domain tools for co-calibration of the sensors
  - Demonstrated in the lab (LCSN)
  - Demonstrated in Helsinki AQ sensor network together with UH
- Tools for drift and malfunction detection
- Uncertainty budget for cocalibration of the sensors under transient conditions



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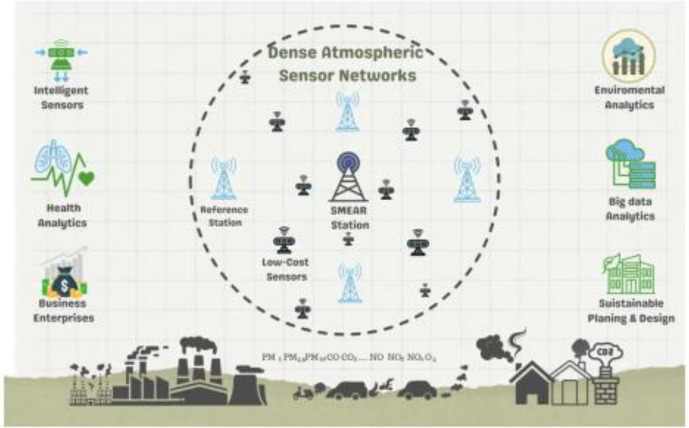
Sensor network metrology: Current state and future directions

Shahin Tabandeh [a], Anupam Prasad Vedurmudi [b], Henrik Söderblom [a], Sara Pourjamal [a], Peter Harris [c], Yuhui Luo [c], Maximilian Gruber [b], MichaeI. Vaa [d], Mads Johansen [d], Martin Koval [e], Peter Friis Østergaard [f], Kruno Milicevic [g], Martha Arbayani Zaidan [h i], Tareq Hussein [h j], Tuukka Petäjä [h], Maitane Iturrate-Garcia [k], Miloš Davidović [l], Marcel van Dijk [m], Gertjan Kok [m], André Xhonneux [n]...Jonathan Pearce [c]

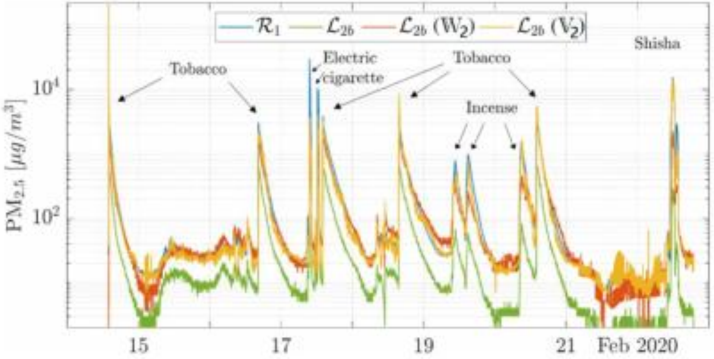
Big picture of Sensor Network Metrology contributed by16 institutes

Henrik Söderblom
Shahin Tabandeh



Intelligent enviRonmental mOnitoring and aNalytics (IRON) group

- Head of the group: Martha Arbayani Zaidan
- Group website: www.helsinki.fi/iron
- Part of Department of Computer Science (CS) and Institute for Atmospheric and Earth System Research (INAR)
- Part of 6G research group led by Prof. Sasu Tarkoma (https://www.helsinki.fi/6gresearch)
- Total active funding ~ € 1.5 Millions
- Research Projects funded by Research Council of Finland, Business Finland, European Research Council (ERC),



Zaidan, M.A., Motlagh, N.H., Fung, P.L., Khalaf, A.S., Matsumi, Y., Ding, A., Tarkoma, S., **Petäjä, T.**, Kulmala, M. and **Hussein, T.**, 2023. Intelligent air pollution sensors calibration for extreme events and drifts monitoring. *IEEE Transactions on Industrial Informatics*, 19(2), pp.1366-1379.

INAR
INSTITUTE FOR ATMOSPHERIC AND EARTH SYSTEM RESEARCH

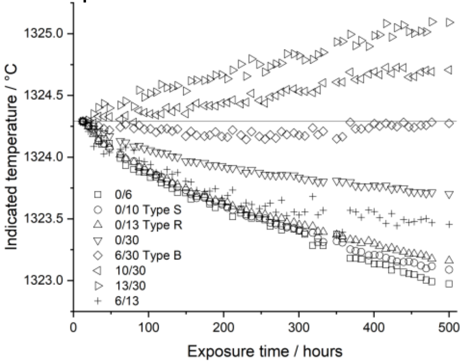
HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

FCAI
Finnish Center for Artificial Intelligence

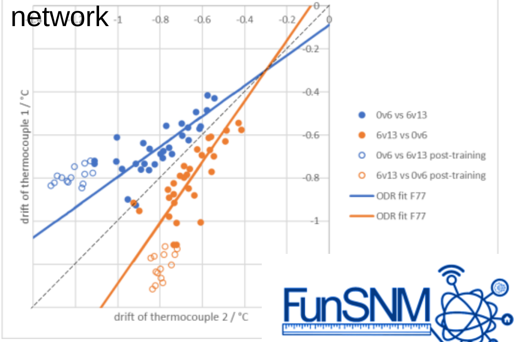
Heat treatment of high value components

- **Jonathan Pearce, Declan Tucker, Peter Harris, Yuhui Luo**
- Thermocouples by far the most commonly used temperature sensor in industry
- Calibration drift is a widely recognized problem
- New method of quantification of drift using multi-wire Pt-Rh thermocouple (each wire having a different composition)
- Fusion of multiple sensors and a validated physical model based on the evaporation of Pt and Rh oxides and the resulting change in wire composition (thermoelectric drift depends on the wire composition)
- The thermocouple is the network
- Several models being developed to mitigate drift – physically based, data driven, hybrids – original idea doesn't work, but new possibilities have opened up

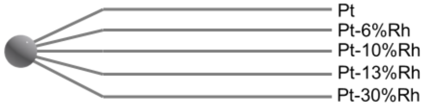
Training data where true temperature is known and invariant



Exploiting linear relationship between drift of pairs of thermocouples in network



$$_{n}C_{r} = \frac{5!}{2! \times (5-2)!} = 10$$

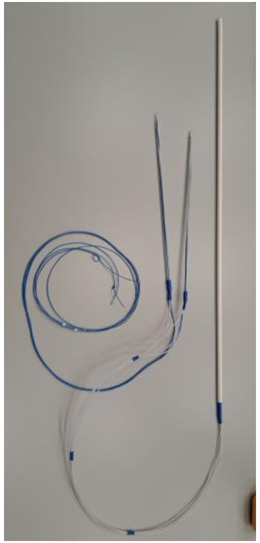


- Presented at IMEKO 2024
- To be presented at Tempmeko 2025
- Case studies from the European project 'Fundamental principles of sensor network metrology', J.V. Pearce, M. Vaa, M. Iturrate-Garcia, S. Tabandeh, IMEKO 2024 XXIV World Congress (paper submitted)
- Measurement uncertainty evaluation for sensor network metrology, P. Harris, P. Ostergaard, S. Tabandeh, H. Soderblom, G. Kok, M. van Dijk, Y. Luo, J. Pearce, D. Tucker, A. Verdurmudi, M. Iturrate-Garcia, Metrology 5(1) 3 (2025) https://doi.org/10.3390/metrology5010003

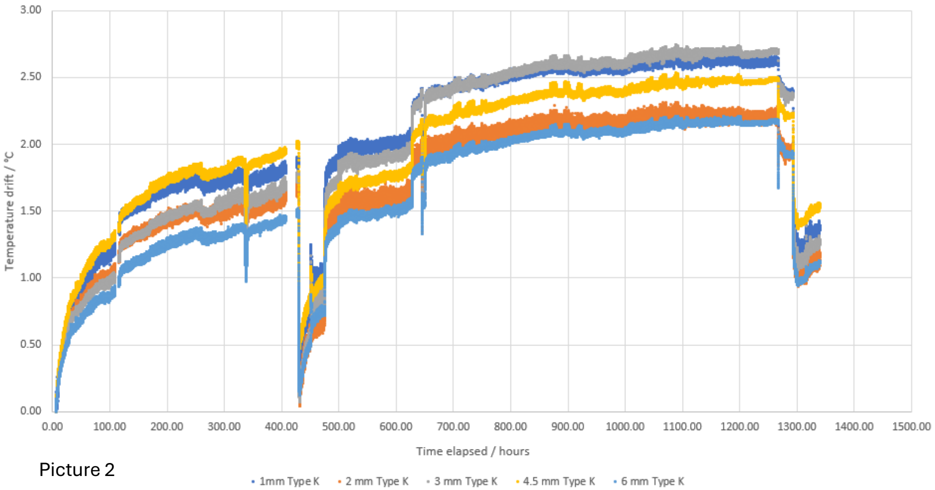
Multiwire thermocouples

Kristjan Tammik:

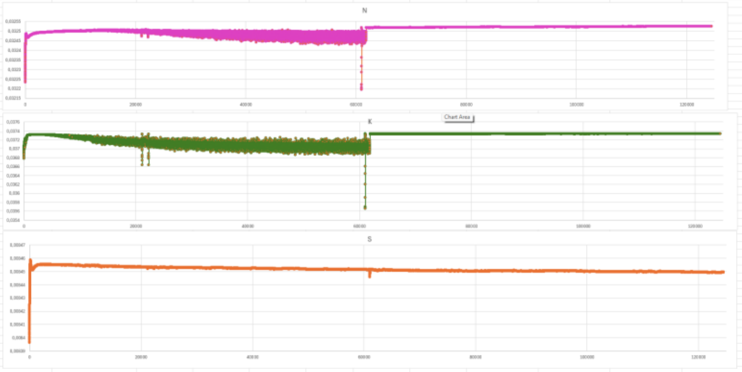
- Construction of base metal multi-wire thermocouples and preparation of commercial type K thermocouples for measurements in collabration with NPL (through Mentoring Scheme Award).
- Setup of measuring system containing of measuring bridge, thermocouples, furnace, cold-junction thermostat, stabilization block.
- Heat treatment of 3 sets of thermocouples (twisted, welded and commercial) and collecting data. Data collecton lasted almost 4 months (from 1. Oct 2024 to 20. Jan 2025)
- All data and observations during measurements has been sent to NPL for calibration drift investigation.



Picture 1



Picture 2



Picture 3

Kruno Miličević

RANDOM RED

- Elements of metrologically consistent approach (table columns) and the critical characteristics (table rows) based on the implementation requirements for the specific sensor network cases.
- Darker green indicates higher relevance, while lighter green indicates lower relevance.

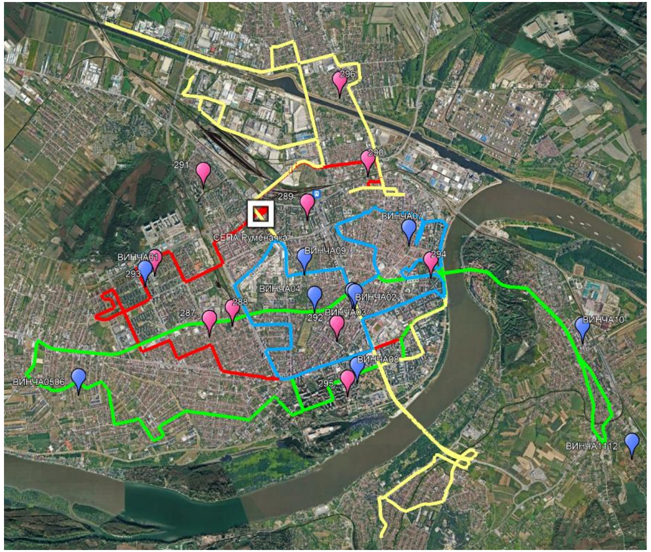
	1. Calibration and Traceability	2. Measurement Uncertainty Evaluation	3. Data Quality and Validation	4. Semantic Interoperability	5. Treating the sensor network as an integrated measurement system	6. Continuous Monitoring and Maintenance
A. Types of Sensors and Measurands						
B. Sensor Configuration and Placement						
C. Data Management						
D. Measurement Accuracy and Reliability						
E. Network Performance						
F. Optimization and Scalability						
G. Interoperability						
H. Cybersecurity and Resilience						
I. Usability and Stakeholder Alignment						
J. Data Quality Assurance						
K. Infrastructure and Integration						
L. Environmental Adaptation						

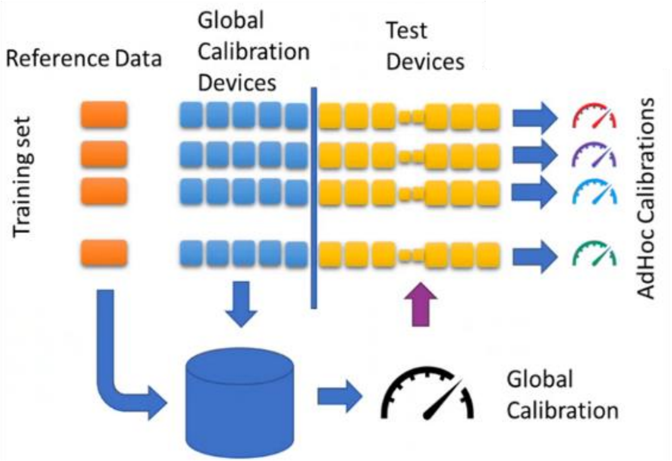
FunSNM

VINS – Vinča Institute, National Institute of the Republic of Serbia, University of Belgrade

Research team: dr Milos Davidovic, VINS PI, and team of VIDIS center (https://vidis-project.org/)

- Completed activities: VINS worked on several important literature reviews and surveys, related to air quality sensor networks and sensor networks in general, and contributed to research and comprehensive review of **state-of-the-art global calibration approaches** used in LCS networks.



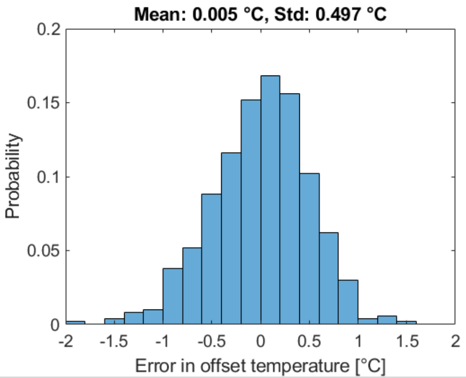


Exciting upcoming activities: VINS in collaboration with METAS is working on expanding typically used collocation calibration scheme to a more traceable, low-cost calibration scheme for air quality low-cost sensors

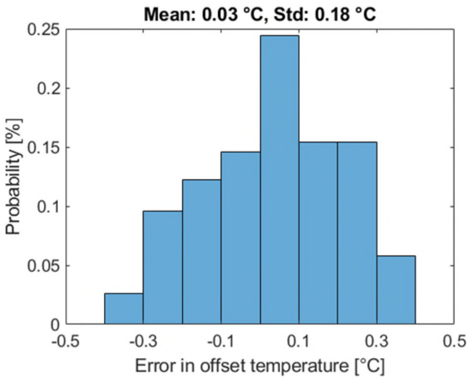
UNSCENTED KALMAN FILTERS FOR DISTRICT HEATING ERROR DETECTION

- Unscented Kalman filters enables state estimation in correlated, non-linear systems with explicit uncertainty evaluation
- Allows for continuously updated system state evaluation with each new set of measurements
  - Continuous trackning of equipment drift
  - Fast detection of critical faults

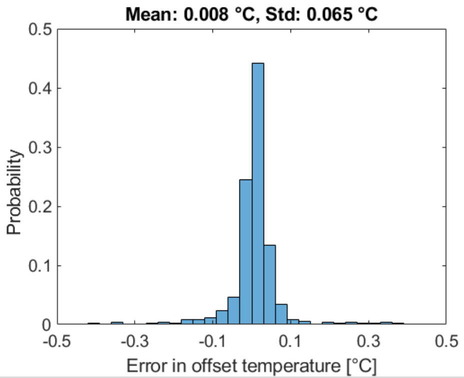
- Analysis on simulated data show theoretical possibility for identifying the absolute error of the utility meter with a standard uncertainty of 0.18 °C
- With known temperature at the beginning of the main pipe, the standard uncertainty of the estimated error at the utility meters can be reduced to 0.065 °C



Initial error distribution of temperature measurements



Error distribution after Kalman filtering for one season



Error distribution after Kalman filtering for one season with known entry temperature into the main pipe

Advances in Smart Buildings

- Development and open-source release (Gitlab) of a Python tool for the automated generation and calibration of room/building models in Modelica language
- Development of software sensors (and corresponding paper + conference proceedings)
- Overview of common ontologies used for buildings and (low-temperature) district heating networks

ALICE2Modelica - Automated Building Model Generation for Building Control and Simulation

Publisher: IEEE Cite This PDF

Maximilian Mork ; Eziama Ubachukwu ; Jakob Benz ; Philipp Althaus ; André Xhonneux ; Dirk Müller **All Authors**

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Gaussian processes and sensor network calibration

João A. Sousa [a], Alistair B. Forbes [b]

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Modelling and determining correlations in sensor networks

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metrology MDPI

Article

Measurement Uncertainty Evaluation for Sensor Network Metrology

Peter Harris [1,*], Peter Friis Østergaard [2], Shahin Tabandeh [3], Henrik Söderblom [3], Gertjan Kok [4], Marcel van Dijk [4], Yuhui Luo [1], Jonathan Pearce [1], Declan Tucker [1], Anupam Prasad Vedurmudi [5] and Maitane Iturrate-Garcia [6]

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