Publishable Summary for 22DIT02 FunSNM
Fundamental principles of sensor network metrology

Overview

Sensor networks are used in many fields but are struggling with data quality of varying degrees, unknown measurement uncertainty and lack of traceability to the SI, limiting their applicability. To overcome these issues, this project will address the metrological aspects of generic sensor networks, covering uncertainty propagation, data quality metrics and SI-traceability. In addition, this project will cover the assessment, infrastructure, and risk analysis of distributed sensor networks alongside software frameworks by developing automated applications. The applicability of the methods, tools, and concepts will be demonstrated in typical real-world sensor networks.

Need

Metrology is facing unexplored challenges introduced by the recent developments in sensors, network architecture, in-situ self- and co-calibration techniques, data routing, processing, and Artificial Intelligence (AI) methods, exemplified by Machine Learning (ML) algorithms based on Deep Learning (DL). Their influence on sensor network technologies ranges from areas, such as air quality monitoring and energy networks, to advanced manufacturing. This comes with its own challenges, due to the large volume of data with innate characteristics, such as velocity, volume, value, variety, and veracity.

The quality assurance of sensor networks is important as described in the following Directives: Directive 2010/75/EU of the European Parliament on Industrial Emissions (integrated pollution prevention and control), Directive 2008/50/EC on ambient air quality and cleaner air for Europe, and Directive 2018/2002 – Amendment of Directive 2012/27/EU on energy efficiency. Therefore, novel metrology including traceability, uncertainty assessment, and new calibration techniques for sensor networks is needed to guarantee the quality of their data.

There is a need to develop novel methods or adaptations of the existing methods for uncertainty propagation in sensor networks and for metrological treatment of sensor correlations in data aggregation applications. The development of methods for metrological assessment of distributed sensor networks is also required to establish the trustworthiness of distributed sensor networks over their entire life cycle. In addition, the automated and online implementation of methods developed for large sensor networks, particularly those with characteristics changing on a relatively short timescale, requires the development of new methods and software tools as well as the adaptation of existing approaches to uncertainty evaluation, data quality assessment and traceability.

There is a clear need to develop reliable and accurate methods for the assessment of data quality and measurement uncertainty in real-world sensor networks, such as:

- Advanced manufacturing requires general research to improve the quality of the network-wide measurement data, obtained from existing sensors to control processes and prevent progressive accuracy loss and degradation of product quality.
- City-wide air-quality monitoring networks need in-situ dynamic calibration capabilities to account for their transient nature, as well as methods to facilitate regular recalibration under dynamic conditions.

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European Partnership Co-funded by the European Union

- With an aim of 80–95 % reduction of greenhouse gases from buildings and workplaces, methods for building management must be found through new and smarter digital tools and software frameworks.

Many other areas have similar challenges with uncertainty propagation in sensor networks, and a combined effort to develop tools will provide a suite of generic tools that can be adapted to a wide range of applications.

Objectives

The overall aim of this project is to provide a metrological basis to sensor networks including uncertainty propagation and data quality methods, an assessment of distributed sensor networks, software frameworks and semantics for large transient sensor networks as well as their demonstration in real-word case studies.

The specific objectives of the project are:

1. To develop reliable and accurate methods for the assessment of data quality and measurement uncertainty in real-world sensor networks. The methods will be suitable for a wide variety of sensor networks and should include the propagation of uncertainties, proper treatment of correlations, and uncertainty-aware sensor fusion. Additionally, to produce metrological guidance for data quality metrics in sensor networks that include not only measurement uncertainty but other common factors that can influence data quality.
2. To extend the results obtained in objective 1 to the case of distributed sensor networks, and to develop reliable and accurate methods for their metrological assessments. The methods will cover a wide variety of sensor networks and geographical distributions (e.g., Smart Grid sensors, IoT networks in Smart Cities). Methods will also consider edge and cloud architectures where sensor data is aggregated locally before communication to other parts of the network.
3. To develop reliable methods for the automated application of the methods in objectives 1 and 2, in large transient networks. This requires novel approaches for the handling of information on the individual sensors, their interaction and metrological characterisation, and includes machine interpretable and metrology-aware descriptions for complex sensor networks using semantic technologies (e.g., ontologies). These novel approaches should integrate metrological information on data quality with traceability, as provided by digital certificates and sensor network data protocols.
4. To demonstrate the practical validity of the methods developed in objectives 1, 2 and 3, in at least 3 real-world case studies (e.g., industrial processing, environmental monitoring, building and utility sectors. Using the results of the case studies to develop end user guidance and software for sensor network metrology. The end user guidance will provide improved measurement reliability including (i) standardised methods for in situ metrology, (ii) the use of the software (iii) the use of metrological redundancy, and (iv) error detection.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by end users (industry, advanced manufacturing, environmental monitoring, and energy), standards developing organisations [e.g., Integrated Pollution Prevention and Control (IPPC), Directive 2010/75/EU, Energy Efficiency Directive 2012/27/EU and Directive 2014/32/EU (MID)], and accreditation bodies.

Progress beyond the state of the art and results

The current state of the art for sensor network metrology is limited to specific applications. For the first time, sensor networks are addressed in a metrologically sound and systemic manner, creating outputs for all areas, where sensor networks are implemented.

Objective 1: At the end of the project, new tools will be available for generic uncertainty propagation in hardware- and software-based sensors, tools for the SI-traceability chain via self- and co-calibration of the sensors, and uncertainty-aware sensor fusion together with drift and detection of malfunctioning sensors. Data quality metrics will also be identified for a generic sensor network that was not previously available. These new tools, by giving traceability and by properly assessing the uncertainty, will broaden the applicability of sensor networks and make the data reliable.

Objective 2: The project will make substantial progress in the characterisation of fixed and mobile distributed sensor networks considering the data aggregation and trustworthiness across their whole life cycle. The infrastructure aspects, e.g., topology, communication, and access, will be addressed and transformed into architecture design criteria that current methods lack. Risk analysis for the sensor networks will be addressed for the first time in a coherent and standardised manner and its results will be collated in publicly available good practice guides.

Objective 3: Automated data handling software frameworks and semantics will be significantly enhanced during the lifetime of the project. This comprises machine-interpretable and metrology-aware descriptions employing semantic technologies. As an outcome, dynamic and distributed measurements in generic large scale transient sensor networks will benefit from the automated methods developed in the project.

Objective 4: Five cases in the project will showcase how the tools developed can be used for improving the state of the art in a suite of representative areas:

a) Uncertainty propagation in sensor networks will assist in significantly reducing the temperature uncertainty in district heating networks, enabling reduction of the supply temperature, and leading to lower distribution losses.

b) The improvements in calibration drift analysis will assist in the development of drift determination in multi-wire thermocouples for high-value products, where even small deviations in process temperature can have a significant impact on product quality.

c) Sensor fusion will aid in the quality verification of gas distribution meters. This will lead to calibrations being performed when needed, rather than at set times, thereby reducing the calibration costs of critical equipment. Metrology for air-quality monitoring networks will be addressed for the first time via automated uncertainty evaluation, data metrics and methods for establishing SI traceability for static and mobile devices. Data aggregation techniques, data fusion methods in the transient heterogeneous environment, and soft sensors will be investigated.

d) Using optimal combinations of physical and software sensors will reduce installation and maintenance costs while potentially gaining accuracy in smart buildings. This will again lead to improved energy management of the buildings.

Outcomes and impact

Outcomes for industrial and other user communities

Outputs from this project are expected to bring significant value to a broad range of industries, ranging from the manufacturing of high-value products to the optimisation of district heating and cost reduction in smart buildings.

Tools developed for the detection of malfunctioning equipment and derivation of information on the sensor drift in situ are relevant for multiple applications and their data quality assessment. This adds value to the manufacturing of high-value products and energy transmission networks.

Good practice guides will directly benefit end users by providing guidance on the metrological assessment of distributed sensor networks with a particular focus on identifying the infrastructure requirements, network architecture, topology and data aggregation for fixed and mobile sensor networks.

The tools developed for uncertainty analysis will enable district heating networks to operate at a much lower supply temperature, significantly reducing heat losses, with immediate impact through financial savings.

The development of data fusion to determine the calibration drift of gas flow meters, individually or in distributed networks, will reduce measurement uncertainty by at least one-third and permit better planning of calibrations.

Novel SI-traceability lowers measurement uncertainties, improves data reliability, and impacts environmental monitoring, with an improved understanding of pollution dispersion, based on static and mobile sensor networks. This informs and empowers decision-makers to monitor and decrease local pollution levels.

Improved knowledge of how to optimally combine hardware and software sensors for smart buildings will reduce installation and maintenance costs while improving accuracy.

Outcomes for the metrology and scientific communities

The metrological and scientific communities will receive input from working groups, such as BIPM JCGM/WG1, where results from this project can be used as input to a potential supplement to the Guide to the Expression of Uncertainty in Measurements (GUM), and inputs to European Metrology Networks, where several groups are currently dealing with aspects of sensor networks.

Additionally, the metrology community will see beneficial outcomes in the tools available for uncertainty analysis of low-cost/low-value sensors in large-volume networks, which are expected to become widespread in the near future. Such sensors are rarely calibrated individually but can bring valuable information when placed in sensor networks.

Outcomes for relevant standards

The project will impact standardisation in several fields due to the generic and widely applicable nature of the research reflected in the use cases. The earliest impact will be on the work programmes of CEN, ISO, IEC, IEEE and WELMEC technical committees and working groups involved in the standardisation related to the industrial, utility, and environmental applications of the use cases studied.

Industry standards such as AMS2750 from Nadcap (National Aerospace and Defence Contractors Accreditation Program) governing heat treatment of high-value components and IEC TC 65/SC 65B/WG5 (Temperature sensors and instruments) can take advantage of the project results. The early impact is expected on the work of ISO/IEC JTC1 SC41 to include metrology and data quality; the documentary standard impacted is expected to be ISO/IEC 30178. The work on the metrological assessment of sensor networks is highly relevant for the IEEE TC10 scope concerned with electronic instrumentation and electrical measurement (several standards e.g., IEEE 1241-2010TM, IEEE 181-2011TM, and IEEE P2414TM).

The standardisation organisations benefiting from the outcomes of the project research and the lessons from the two utility use cases include the WELMEC WG7 'Software' with respect to software and IT components, and WG11 "Gas and Electricity Meters", responsible for a harmonised approach towards legal metrology issues for utility meters. At the CEN level, results are expected to impact the work of CEN TC 176 regarding standardisation in the field of heat meters.

The outputs of this project will be disseminated to CEN-264-WG-42. This committee writes specifications and standards for the validation of air quality sensors, including statistical components. The results of the project are foreseen to impact CEN/TS 17660-1 and the draft technical specification CEN/TS 17660-2 (TC-264-WI-00264179), and possibly future standards on the operation of air quality sensor networks that CEN 264 WG 42 is expected to initiate.

Longer-term economic, social and environmental impacts

Economic

An estimated 0.54 EJ of energy is lost in European district heating networks each year. A general reduction of the supply temperature from 85 °C to 80 °C will potentially cause a 6 % reduction in heat loss to the ground, resulting in energy savings corresponding to 33 PJ/year, reducing CO2 emissions by 3 million tonnes per year, and providing financial savings of 2 billion euros.

Extra sensors, required to further reduce supply temperatures without creating health risks, have a potential European market of up to €280 million for hardware components alone, with similar potential revenues for software solutions. In the gas sector, the EU imported 88 billion m^3 in the first quarter of 2022, valued at €78 billion. If a current 1 % annual drift in sensor output can be reduced by 30 % through data fusion techniques, a potential €1 billion can be saved per year.

Environmental

Air pollution, linked to 300,000 premature deaths annually in the EU and millions more worldwide, can be monitored more reliably, utilising the tools developed in this project. This will enable decision-makers to focus their efforts. The outcome of this project will support the intention of the EU of becoming CO2-neutral by 2030, by improving the control and maintenance of utility networks, and by reducing energy consumption in manufacturing, and industrial processing, which accounts for 22 % of European greenhouse gas emissions (joint second highest contributor together with domestic transport; energy supply is the most emitting at 26 %). The improvement in thermometry alone will thus directly improve fuel efficiency and reduce atmospheric emissions.

Social

In the present situation, where fossil fuel prices in Europe have increased significantly, low-income households in Europe (estimated 11 million inhabitants) will have to spend at least 50 % of their current expenditures to compensate for increasing energy prices. Solutions developed in this project will significantly enhance the efficiency of energy distribution networks, resulting in an associated impact on energy savings and prices.

List of publications

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This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

<table>
<tr><td colspan="2">Project start date and duration:</td><td>1 September 2023, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Shahin Tabandeh, VTT   Tel: +358 50 313 3634   E-mail: shahin.tabandeh@vtt.fi
Project website address: not available yet</td></tr>
<tr><td>Internal Beneficiaries:
1. VTT, Finland
2. CMI, Czechia
3. DTI, Denmark
4. FORCE, Denmark
5. IPQ, Portugal
6. LNE. France
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