European Partnership on Metrology
Call 2024 –Digital Transformation, Green Deal, Normative and Research Potential

Selected Research Topic number: **SRT-d02**
Version: 1.1

Title: Large-scale virtual calibration of MEMS sensors for sensor networks

Abstract

Micro-electro-mechanical systems (MEMS) sensors are widely used in large sensor networks for many applications, such as structural and environmental monitoring. The mass production of MEMS, often in the order of millions/week, requires huge, costly and time-consuming calibration processes which frequently result in a lack of metrological traceability. The solution to this, could be virtual calibration methods using Bayesian statistical tools and Machine Learning (ML) methods, thereby substituting, or complementing traditional laboratory calibrations. Such virtual calibration methods should drastically reduce both time and cost, as long as the methods can provide accurate and robust traceability at acceptable uncertainty levels, for MEMS sensors and large sensor networks.

Keywords

MEMS, large-scale calibration, big-data, Bayesian inference, virtual calibration, measurement uncertainty, structural monitoring

Background to the Metrological Challenges

In contemporary technological applications, low-cost and low-power MEMS sensors play a pivotal role in variety of domains, like in sensor networks for industry, in the automotive and construction sectors, and for structural and environmental monitoring. The widespread use of MEMS and large sensor networks aligns with the ongoing digital transformation in these sectors. But to ensure the safety and functionality of the operations governed by large sensor networks, the data supplied from the sensors must be reliable and accurate. Thus, there is an urgent need to establish large-scale calibration methods for MEMS sensors in sensor networks.

Existing periodic, in-situ calibration and verification of large (low-cost) sensor networks, presents several challenges: (i) the sensor networks require frequent calibration to maintain accuracy, (ii) the calibrations are often in harsh or dynamic environments, (iii) the location of MEMS sensors may be difficult to access, especially in remote or hazardous environments and (iv) this results in time-consuming and resource-intensive calibrations given the number of MEMS sensors in the networks, up to thousands at a time.

Current literature suggests that solutions for achieving large-scale calibration of MEMS sensors could be realised via either (i) in-line calibration systems or (ii) virtual (statistical) calibration methods, although practical implementation is incomplete. In-line calibration would have the advantage of calibrating all MEMS sensors during production, by using traceable methods defined by the manufacturer. However, the disadvantages include challenges in ensuring standard calibration procedures and impartiality.

In contrast, large-scale virtual calibration methods have the benefit of requiring very few experimental calibrations and would allow accredited calibration laboratories to conduct these in adherence to standard procedures and then extend the results to millions of sensors. The potential for using virtual calibration methods has been highlighted by both BIPM's Consultative Committee for Acoustics, Ultrasound, and Vibration (CCAUV) and the European Metrology Network for Mathematics and Statistics (EMN Mathmet). Preliminary work on the use of statistical Bayesian approach for calibration purposes has recently been proposed, however, the work is in the early stages and lacks experimental validation. The mathematical developments of the Bayesian approaches are also limited. Further to this, the use of large-scale virtual calibration and

Bayesian approaches needs to be evaluated in terms of balancing the potential benefits and disadvantages (i) both computationally and practically and (ii) cost versus target uncertainty and accuracy.

Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the protocol.

The proposal shall focus on metrology research necessary to support digital transformation in the large-scale virtual calibration of MEMS sensors in sensor networks.

The specific objectives are

1. To develop virtual calibration methods using Bayesian statistics and sampling techniques for large batches of MEMS sensors (up to millions) with reduced time and costs compared to existing one-to-one calibration methods. Then, to evaluate the reliability of virtual calibration method via the introduction of novel metrics that account for (i) various statistical parameters and (ii) the characteristics of the MEMS manufacturing processes, including strategies for balancing cost versus uncertainty.
2. To validate the virtual calibration methods from Objective 1, using large batches of MEMS accelerometers ($100 < n < 1000$) in two ways: (i) bootstrap comparison with expected theoretical values, and (ii) experimental measurement comparison with one-to-one laboratory standard calibrations (e.g., ISO 16063-21). In addition, to develop experimental calibration methods for the dynamic, simultaneous calibration of large numbers of MEMS accelerometers ($10 < n < 100$) e.g. using multi-sine or multi-axial excitation. Then to compare the developed experimental calibration methods with the virtual calibration methods. The target relative difference between the experimental and virtual calibration methods is < 5 %, and the target normalised error is < 0.8.
3. To compare the virtual calibration method form Objective 1 to existing, standard metrological calibration methods using an in-situ large sensor network of hundreds of calibrated MEMS accelerometers. This should be done in real-world case study scenarios (e.g. structural monitoring of buildings) and the target relative difference for detected vibrational signals is < 5 %.
4. To develop metrological methods for the continuous calibration and verification of MEMS in large sensor networks, using ML and statistical algorithms to analyse big-data physical signals. The target uncertainty for the continuous calibration and verification method is < 5 %, and it should incorporate physics-based and data-driven models for sensor-drift detection together with the in-situ, self, and co-calibration processes. The continuous calibration and verification method must also address (i) uncertainty propagation, (ii) appropriate correlation treatment, and (iii) uncertainty-aware sensor fusion to ensure SI-traceability within the MEMS network.
5. To develop guidelines and recommendations for the adoption of virtual calibrations for large batches of MEMS sensors and large-scale sensor networks. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs/DIs, calibration laboratories), standards developing organisations (ISO/TC 108, BIPM CCAUV) and end users (semiconductor, sensor network and MEMS manufacturers).

These objectives will require large-scale approaches that are beyond the capabilities of single National Metrology Institutes and Designated Institutes. To enhance the impact of the research, the involvement of the appropriate user community such as industry, standardisation and regulatory bodies, and other European Partnerships is strongly recommended, both prior to and during methodology development.

Proposers should establish the current state of the art and explain how their proposed project goes beyond this. In particular, proposers should outline the achievements of the EMPIR 17IND12 Met4FoF project and how their proposal will build on this.

Proposers should note that the programme funds the activity of researchers to develop the capability, not the required infrastructure and capital equipment, which must be provided from other sources.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 1.9 M€ and has defined an upper limit of 2.4 M€ for this proposal.

EURAMET also expects the EU Contribution to the external funded beneficiaries to not exceed 35 % of the total EU Contribution across all selected projects in this TP.

Any industrial beneficiaries that will receive significant benefit from the results of the proposed project are expected to be beneficiaries without receiving funding or associated partners.

Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the 'end user' community, describing how the project partners will engage with relevant communities during the project to facilitate knowledge transfer and accelerate the uptake of project outputs. Evidence of support from the "end user" community (e.g. letters of support) is also encouraged.

You should detail how your proposal's results are going to:

- Address the SRT objectives and deliver solutions to the documented needs,
- Feed into the development of urgent documentary standards through appropriate standards bodies,
- Facilitate improved industrial capability, or improved quality of life for European citizens in terms of personal health, protection of the environment and the climate, or energy security,
- Transfer knowledge to semiconductor and MEMS manufacturing and construction and environmental monitoring sectors.

You should detail other impacts of your proposed JRP as specified in the document "Guide 4: Writing Joint Research Projects (JRPs)"

You should also detail how your approach to realising the objectives will further the aim of the Metrology Partnership to develop a coherent approach at the European level in the field of metrology and include the best available contributions from across the metrology community. Specifically, the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of EURAMET Member States whose metrology programmes are at an early stage of development to be increased
- organisations other than NMIs and DIs to be involved in the work.

Timescale

The project should be of up to 3 years duration.

Additional information

The links provided in this section are only correct at the time of publication up until the end of the Call year.

The references below were provided by PRT submitters; proposers should therefore establish the relevance of any references.

[1] EMN for Mathematics and Statistics in Metrology Strategic Research Agenda
https://www.euramet.org/research-innovation/metrology-partnership/strategic-research-and-innovation-agendas