Publishable Summary for 17IND12 Met4FoF
Metrology for the Factory of the Future

Overview

The "Factory of the Future" (FoF) as an inter-connected production environment with an autonomous flow of information and decision-making constitutes the digital transformation of manufacturing to improve efficiency and competitiveness. Transparency, comparability and sustainable quality all require reliable measured data, processing methods and results. This project established a metrological framework for the complete lifecycle of measured data in industrial applications, including calibration capabilities for individual sensors with digital pre-processed output and uncertainty quantification associated with machine learning (ML) in industrial sensor networks. The project focused on two very common challenges in manufacturing; (i) process optimisation and (ii) predictive maintenance; which were represented by the 3 different testbeds chosen for the project's demonstrators. The project successfully implemented its outputs in the 3 different testbeds (using different types of sensor networks in each) in order to demonstrate the practical applicability of the outputs and to promote future up-take by industry.

Need

Traceable calibrations, harmonised treatment of measurement uncertainties, and industrial standards and guidelines are the major components of a comprehensive metrological infrastructure that has enabled globalised manufacturing and international trade. Digitalisation and data science are rapidly changing almost all aspects of this landscape: e.g. sensors are becoming smart, large networks of sensors are being used together with ML algorithms to make automated decisions and manage production processes. The combination of these technological elements constitutes the FoF, a paradigm that is evolving rapidly worldwide.

According to the 2016 UK "Workshop on Data Metrology" and other similar surveys, one of the top priority industrial needs in the FoF is data quality. This project addressed the need for data quality by focussing on the measurement uncertainty framework supporting such a metrological infrastructure. In order to address the complete flow of information this infrastructure needed to cover the traceable calibration of smart sensors whilst taking into account dynamic effects, the metrological treatment of complex sensor networks, uncertainty evaluation for the data aggregation and decision-making methods. Previous projects have developed the foundation of some of these aspects: EMRP IND09 established a metrological infrastructure for analogue dynamic measurement of mechanical quantities; EMPIR 14SIP08 implemented the mathematical methods from EMRP IND09 into software tools and guidelines for industrial end users; and EMRP ENG63 developed mathematical methods for sensor network metrology focusing on electrical power grids.

However, the outputs from these preceding projects (and hence calibration facilities) needed further work to include digital-only sensors, which required this project to develop new concepts to deal with the internal time keeping of sensors. Cost-efficient traceable calibration of Micro Electro Mechanical Systems (MEMS) sensors for ambient conditions is also needed to associate their output with reliable uncertainties. Further to this, methods for sensor network metrology needed to be extended and uncertainty-aware ML methods need to be developed to address uncertainty evaluation in industrial sensor networks.

Objectives

The overall goal of this project was to establish the metrological infrastructure required for quality assurance and traceability in the FoF by taking into account measurement uncertainty from the traceable calibration of individual sensors through to ML data aggregation methods. The objectives of the project were:

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

1. To develop calibration methods for industrial sensors of dynamic measurements such as acceleration, force and pressure with digital data output (data streams) and internal digital pre-processing, including the extrapolation of the measurement uncertainty from individually calibrated sensors to other individuals of the same type by means of co-calibration and statistical modelling.
2. To develop and demonstrate methods enabling digital sensors to provide uncertainty and/or data quality information together with the measurement data.
3. To develop a cost-efficient in-situ calibration framework for MEMS sensors measuring ambient temperature for their integration into an industrial sensor network with metrological quality infrastructure.
4. To develop and assess data aggregation methods for industrial sensor networks based on machine learning and efficient software architectures, addressing synchronisation of measurements, making use of redundancies of measurements, taking into account uncertainty from calibration and network communication issues, including strategies for balancing cost versus uncertainty and explore methods to identify the measurement coverage and accuracy required for process output targets.
5. To improve existing industry-like testbeds for sensor networks in manufacturing environments towards the implementation of a metrological quality infrastructure and to facilitate the take up of the project outputs by the stakeholders, especially the manufacturing industry.

As part of objective 5, the project used 3 different testbeds with different types of sensor networks:

- The SPEA Automatic Test Equipment (ATE) for MEMS temperature sensor testing uses a network of reference temperature sensors, where the optimal implementation and usage of this sensor network determines the efficiency and reliability of the ATE results.
- The STRATH testbed considers radial forging using pre-heated metallic material and vibrating hammers. The testbed will be used to try and optimise the heating and forming process based on a range of different sensors in order to improve the production output quality.
- The ZEMA testbed uses a range of sensors measuring different quantities for end-of-line tests and condition monitoring methods for electromagnetic cylinders.

For all three testbeds, uncertainty in the whole flow of information, from the individual sensors to the data analysis output, was consistently considered.

Progress beyond the state of the art

Calibration framework for sensors with digital pre-processed output

Measurands in the FoF are typically time-dependent, thus requiring methods from dynamic metrology which were developed, for example, in EMRP project IND09. In particular the reliable calibration of the sensor phase is an important issue for time-dependent measurands. In FoF environments, sensors can provide digital-only time-dependent output and will have internal signal processing capabilities. This would make phase calibration challenging, because the internal time keeping of the sensor is no longer managed by the calibration system, making new concepts for the calibration of such sensors necessary. Before the start of this project, the dynamic calibration facilities developed in EMRP IND09 were not ready to handle such “smart sensors” with digital output and/or with internal pre-processing. Therefore, this project extended NMI-level dynamic calibration facilities to include sensors with digital output and internal pre-processing. The project developed a digital acquisition unit (DAU), which takes the digital output from the device under test and generates precision timestamps with known uncertainty from a GPS time signal. This allows the measurement uncertainty contribution corresponding to the extension of the existing calibration setup for analogue sensors to be relatively small.

The project’s concept works well for both digital sensors with sample-by-sample output and with the batch-wise provision of data. The DAU can also be used outside the calibration setup to integrate digital sensors into a sensor network. The DAU can then provide certain smart features, such as the communication of units of measurement in a digital SI (D-SI) format or to a digital calibration certificate (DCC) as developed in the 17IND02 SmartCom project (which this project collaborated with). Together with the framework for the efficient implementation of sensor network data analysis, the DAU can be combined to produce a proof-of-concept

"Smart Traceability" sensor, communicating its measured values and the associated measurement uncertainty online.

In many Industrial Internet of Things (IIoT) environments, MEMS are used for measuring ambient conditions owing to their flexibility and cost-efficiency. However, reliable calibration information is required in order to incorporate their information into a quality-ensured FoF. Before this project there was a lack of a corresponding metrological infrastructure that met the needs of industrial stakeholders as well as the metrological requirements for traceability to SI. Therefore, this project developed and validated the first ever automated testbed equipment (ATE) at the SPEA testbed for traceable in-situ calibration of MEMS temperature sensors using an optimised network of reference sensors in an automated test environment. As part of this work a so-called reference fixture, which contains several reference sensors, was calibrated in a laboratory traceable to the SI. This fixture was then used to provide traceable batch calibration of MEMS sensors, by mounting the fixture on the ATE machine. The setup was then validated and further optimised based on simulation analyses.

Metrology for industrial sensor networks

Metrological frameworks for sensor networks are at a comparatively early stage of development, with previous projects e.g. EMRP ENG63 only beginning to address their challenges. But in the FoF decisions will be based on measurements from a diverse network of sensors and therefore, these measurements will need to be combined using ML methods in order to optimise manufacturing efficiency, prevent faults and to assess production process quality or degradation of machines and tools.

This project advanced and extended sensor network metrology to deal with network communication issues in FoF environments. The project did this by taking into account specific requirements such as sensor capabilities and online data analysis and decision-making. The project then combined the outcomes of the calibration framework for digital sensors into networks of sensors. The project also outlined generic modelling approaches that compensated for sensor models, timing issues, synchronisation, and redundancy. Mathematical-statistical methods for the mitigation of jitter and other timing issues were also developed by the project.

Redundancy in a network can be used in a sensor network, if it is known. Therefore, this project reviewed existing methods from literature, focusing on those taking uncertainties into account. Based on these methods, data sets from the project's testbeds were analysed for the dependence of uncertainty on the removal of sensors.

FoF testbed implementations

This project went beyond the state of the art by extending three existing industrial testbeds in order to create a metrological framework for digital sensors and ML for sensor network analysis. The 3 testbeds were: (1) the SPEA automated test equipment for MEMS temperature calibration was used to perform SI-traceable testing of temperature MEMS sensors, (2) the radial forging testbed at STRATH and (3) the ZEMA test bench for end-of-line production tests and condition monitoring of electromechanical cylinders. Testbeds (2 STRATH) and (3 ZEMA) were equipped with the "Smart Traceability" prototypes. Testbed (1 SPEA) was extended with the development of a reference fixture for MEMS batch calibration. Moreover, the project made available selected data sets generated by these testbeds in order to support the development of ML in metrology.

Results

Objective 1: To develop calibration methods for industrial sensors of dynamic measurements such as acceleration, force and pressure with digital data output (data streams) and internal digital pre-processing, including the extrapolation of the measurement uncertainty from individually calibrated sensors to other individuals of the same type by means of co-calibration and statistical modelling.

The project developed the necessary basic concepts, terminology and specifications for calibration methods for industrial sensors of dynamic measurements. As a first step, the project developed a micro-controller (µC) board that can hold digital sensors and provide time-stamping traceable to the SI. A communication interface based on Protobuf-Messages connects the µC board to upstream systems, that are running the agent-based framework (ABF) software also developed within the project. The project's ABF was developed to enable easy integration with data analysis method developments and can also provide the measurement information in a large range of protocols for end users. For example, the ABF has been successfully used with OPC-Unified Architecture (a widely used machine to machine communication protocol for industrial automation) to provide data streams from the project's µC board to connected PCs.

To enable the traceable and secure communication of measurement data from the µC board, a collaboration was set-up with the EMPIR project 17IND02 SmartCom and the 17IND02 project's D-SI data model was integrated with this project's ABF. The software corresponding to the µC board and the 17IND02 adaption to the ABF has been published on the project's open source repository on GitHub (https://github.com/Met4FoF).

The first test application of the project's newly developed hardware (i.e. the µC board) was a dynamic calibration as part of an extension to the existing acceleration calibration facilities at PTB. As part of this, the µC board provided an additional ADC channel which samples (and traceably timestamps) a dedicated synchronisation signal in parallel to the Device Under Test's (DUT's) digital output. The first prototypical phase response measurements were successfully performed with the newly developed hardware and extended acceleration calibration facilities. The project's newly developed hardware was also successfully integrated in the dynamic calibration facilities at CEM.

A second test application of the project's newly developed hardware was via the integration of calibrated MEMS sensors for temperature and acceleration into the testbeds at ZEMA and STRATH. The successful integration in the two testbeds enabled them to include calibrated digital sensors for additional applications and data analyses.

Objective 2: To develop and demonstrate methods enabling digital sensors to provide uncertainty and/or data quality information together with the measurement data.

The project developed a proof-of-concept "Smart Traceability" sensor that could provide measured values together with their associated uncertainty and other relevant data quality information. The project did this by extending a conventional sensor with a "Smart-up Unit". In addition, the project further developed the software from EMPIR project 14SIP08 by extending the corresponding software library *PyDynamic* such that measurement data communication from the Smart-up Unit to a connected PC can be processed in a data streaming environment. Furthermore, *PyDynamic* was extended to include a continuous integration (CI) workflow for automated software quality assurance. The central software repository on GitHub connects PyDynamic and the other software developments from this project to an implementation of the ABF developed in objective 1.

The project equipped the testbed at ZEMA with digital-only sensors for acceleration and temperature with the Smart-up Unit. The digital sensors were calibrated at PTB and INRIM with support from SPEA, and they provided their data via the µC board (from Objective 1) to the data acquisition system (of ZEMA). A similar installation of calibrated, digital-only sensors for acceleration and temperature with a Smart-up Unit was also carried out for the testbed at STRATH. Both testbeds are now able to produce data sets from digital sensors together with reliable uncertainty statements. The project's GitHub repository also contains examples on how to use the ABF and methods from the extended *PyDynamic* library for the analysis of this data.

Objective 3: To develop a cost-efficient in-situ calibration framework for MEMS sensors measuring ambient temperature for their integration into an industrial sensor network with metrological quality infrastructure.

The project has developed a novel automated test equipment (ATE) at the SPEA testbed for the traceable in-situ calibration of MEMS temperature sensors using a network of reference sensors in an automated industrial test environment. The new ATE setup was first designed and then implemented in the SPEA testbed so that it could be used to provide traceable calibration of on-board temperature sensors for a reference fixture.

Analysis of the data from the ATE and simulations have been carried out and the project used these to further optimise this novel ATE calibration setup. The optimised ATE setup uses on-board temperature sensors to generate temperature mapping for the calibration of the MEMS sensors.

Traceability of the novel ATE calibration setup was achieved by a calibration of the reference fixture at INRIM, which can now be offered as a novel calibration service. Manufacturers of MEMS temperature sensors can use the ATE calibration setup with a calibrated reference fixture to provide calibrated sensors to their customers. These customers can then integrate the calibrated MEMS sensors into their sensor network, including statements for traceability. Using methods from Objective 2, this information can be used to achieve uncertainty-aware data processing and machine learning such industrial sensor networks.

Objective 4: To develop and assess data aggregation methods for industrial sensor networks based on ML and efficient software architectures, addressing synchronisation of measurements, making use of redundancies of measurements, taking into account uncertainty from calibration and network communication issues, including strategies for balancing cost versus uncertainty and explore methods to identify the measurement coverage and accuracy required for process output targets.

The project developed and tested generic mathematical models and several uncertainty evaluation approaches for industrial sensor networks based on ML. In particular, methods for feature extraction (i.e. the first step in ML) were extended with uncertainty propagation (i.e. the effects on a function by a variable's uncertainty). The project also derived several approaches for the assessment and exploitation of redundancy in sensor networks and applied the approaches to testbed data sets from Objectives 1 & 2 [5]. Based on models of the data collected by digital sensors (subject to noise and jitter effects), methods were also developed to account for timing and synchronisation issues. These methods were then implemented in an update to the project's ABF software library in order to allow flexible use of a variety of sensor networks. The project's updated ABF now contains a comprehensive set of tools for simulation and analysis of heterogeneous sensor networks.

Measurement analysis for sensor networks in the FoF is typically based on ML methods for decision-making. To bring metrology into this area, the uncertainty associated with raw data streams must be taken into account by the ML methods applied. To address this the project investigated whether the methods used for the STRATH and ZEMA testbed data could be extended to take into account measurement uncertainties. The results showed that, in principle, the integration of measurement uncertainty is possible. For the ZEMA testbed uncertainty propagation for the feature extraction as the first step of ML was developed and implemented in the extended *PyDynamic* library (Objective 2). Novel Bayesian feature selection methods as well as uncertainty propagation for the existing methods at the ZEMA testbed were also successfully tested. Finally, classification – the last step of ML at the ZEMA testbed – was extended with an uncertainty propagation. Hence, for the whole data lifetime at the ZEMA testbed uncertainties associated with the data can be made available.

The same feature extraction methods with uncertainty propagation were applied to the STRATH testbed data. For the subsequent ML regression, a variety of Bayes ML methods were investigated. However, more research is needed for the STRATH testbed to identify a suitable sensor setup and ML pipeline combination in order to achieve a sufficient regression result.

Data analysis for the SPEA testbed differed from that for the ZEMA and STRATH testbed in terms of modelling. For the SPEA testbed an interpolation of the temperature field between the reference temperature sensors is required to obtain reference values for the calibration of the MEMS sensors under test. Gaussian probabilistic interpolation was successfully applied, supported by a numerical simulation of the heat distribution using the digital model of the ATE.

To increase end user up-take of the project's developments, relevant data sets were made publicly available on Zenodo on a dedicated Met4FoF community page (https://zenodo.org/communities/met4fof/). Web-based tutorials for using the data sets are also available, e.g. a tutorial webinar on the updated ABF system and a webinar for the application of ML to the ZeMA data set have been recorded and uploaded on the project website and integrated with the project's GitHub repository.

Impact

This project had a joint stakeholder advisory board (SAB) together with the project 17IND02 SmartCom. The SAB included 10 partners from industry, academia and standardisation, such as INESC-MN (a Portuguese public research organisation in the field of microsystems and nanotechnology), MESAP (an Italian Innovation Cluster with 267 Members, active in manufacturing, automotive and aerospace), SPEKTRA (a German company that designs, manufactures and sells calibration systems as well as measuring and test equipment for vibration sensors), TNO (the Netherlands Organisation for Applied Scientific Research), the University of Sarajevo and VDI/VDE (VDI = Association of German Engineers and VDE = Association for Electrical, Electronic and Information Technologies). Input from the SAB has helped to decide the most suitable sensors and interfaces for the project and helped to ensure that the project's outputs are relevant for end users. Together with the SAB member TNO, the project presented a joint publication at the 2019 IMEKO TC10 conference, about the implementation of continuous quality concepts in research.

To increase the uptake of the mathematical methods developed in the project, a public GitHub repository was launched (https://github.com/Met4FoF). This repository connects the software developments from the project and uses modern software quality principles with CI technologies. All partners involved in developing software code regularly added to this repository, and it was recently presented at "deRSE19 - Conference for Research Software Engineers in Germany" in June 2019 in order to promote its uptake by end users.

Impact on industrial and other user communities

This project's outcomes will impact industries that use sensor networks, in particular those using digital sensors for monitoring mechanical quantities such as acceleration, force and pressure. They will support the provision of sensor manufacturers with the traceability needed for sustainable and reliable smart factories and enable them to meet the increasing demand for the provision of measurement capabilities with internal pre-processing. The "Smart Traceability" sensors (Objective 2) developed in this project are also applicable to other sensor types and data post-processing tasks and can be used to support the use of calibration information and measurement uncertainty evaluation (Objective 4) into the post-processing data element of a "Smart Sensor". To support this impact, all software written by the project for the Smart-up Unit (Objective 2) has been made available as open source.

Due to their cost-efficiency and versatility, MEMS are increasingly used in the IIoT, and the in-situ calibration framework for MEMS temperature sensors developed in this project (Objectives 1 & 3) were successfully demonstrated in industrial testbeds to support industrial end-user use. The novel possibilities for using ATEs for batch calibration of MEMS temperature can now be offered by partner SPEA as a commercial product. The first interested customers have already approached SPEA during the project, and more are expected to follow. Moreover, the calibration framework for temperature measurements (Objective 3) will be transferrable to humidity measurements as well as to the testing of other MEMS sensors regarding their temperature and humidity dependence. To support this work, the project's SAB included an expert in MEMS sensors; the Institute for Systems and Computer Engineering, Technology and Science -Microsystems and Nanotechnology (INESC-MN).

The large amounts of data that are gathered in inter-connected manufacturing environments can only be analysed usefully by automated application of ML methods for feature extraction and information aggregation. However, in order to gain trust in the automated data analysis routines, data quality has to be taken into account. Therefore, the methods developed in this project (Objective 4) will support reliable uncertainty assessment together with data measurements, as well as simplified data management with in-situ sensor identification and sensor data communication. For example, the measurement data communicated from Smart-up Units to connected PCs was combined by this project with *PyDynamic* routines adapted to work in a data streaming environment (Objective 2).

With the combination of metrology for digital sensors, industrial sensor networks and the respective data analysis, the whole traceability chain can become digitally enabled. Practical demonstrations of this project's approaches were shown by their implementation in the SPEA, ZEMA and STRATH industrial testbeds. This project and the project 17IND02 SmartCom also developed a demonstrator based on the Smart-up Unit (Objective 2), the 17IND02 SmartCom digital communication guidelines and this project's data analysis methods (Objective 4). The demonstrator was an enriched data set from the ZEMA testbed, extended with the Smart-up Unit (Objective 2). Enrichment of the data set was carried out using the 17IND02 SmartCom digital communication guidelines to achieve a fully machine-readable metadata of the data set, including machine-readable representation of units of measurements.

Further to this, PTB is collaborating in two nationally funded research projects in Germany to combine metrology for sensor networks with asset administration shell approaches, standardised as "RAMI4.0", and with quality of data semantics in industry 4.0, respectively. The nationally funded projects "AAS-based modelling for the analysis of variable CPS" (BMBF FAMOUS) and "Secure and robust calibrated measuring systems for the digital transformation" (BMWi GEMIMEG-II) will implement several developments from this project (in particular from Objective 4) in additional industrial testbeds.

Impact on the metrology and scientific communities

In many applications, use of several low-quality sensors combined with intelligent data analysis is preferred to a small number of high-quality sensors, e.g. to reduce cost or increase robustness through redundancy. The results of this project on taking into account the uncertainty associated with individual sensor's data (Objective 4) in the data analysis will help to balance costs versus quality and increase the uptake of metrological principles in FoF networks. Moreover, the methods developed for the calibration of MEMS sensors (Objective 3) will provide new approaches for traceable in-situ calibration of low-cost sensors. To support this, the project has already successfully demonstrated the use of its Smart-up Units (Objective 2) concept as a basis for a simple implementation of MEMS sensors in the ZEMA and STRATH testbeds.

ML development relies on the availability of realistic and well-documented data. Therefore, test data sets (Objectives 1, 2 & 3) from the 3 testbeds used in this project were used for further developments for uncertainty evaluation in ML. Guidelines and training courses on this work were produced by the project to increase the application of ML in metrology by the scientific community. For example, the project's training courses included (i) Machine learning tutorials for the ZeMA dataset (July 2019), (ii) Data analysis and machine learning for ZEMA data sets and Data analysis and machine learning for STRATH data sets (both October 2019), (iii) Machine learning workshop with ZeMA machine learning toolbox (March 2021) and ZEMA/STRATH Testbed Workshop (September 2021).

The project has also been presented to the metrology and scientific communities 26 times at conferences e.g. Congres International de Metrologie (CIM 2019), the International Conference on Machine Learning (ICML 2020), Advanced Mathematical and Computational Tools in Metrology and Testing International Conference (AMCTM 2020 & 2021), Sensor and Measurement Science International (SMSI 2021), Mathematical and Statistical Methods for Metrology (MSMM 2021), IMEKO 2021 World Congress, and the European Centre for Mathematics and Statistics in Metrology (MATHMET).

Finally, the project has produced 9 open access proceedings, contributions to books and publications in journals such as the Journal of Sensors and Sensor Systems (JSSS) and Sensors

Impact on relevant standards

Existing standards for calibration of sensors, e.g. ISO 16063 for the calibration of vibration and shock sensors, need to be revised to account for digital output data streams. Therefore, the project has promoted the results of its metrological framework for digital sensors within the standardisation community and provided input to relevant standardisation groups, such as ISO/TC 108 Mechanical vibration, shock and condition monitoring WG34 dealing with acceleration, force and pressure.

Project partners involved in relevant standardisation bodies have also presented the project's outputs to BIPM Consultative Committee for Thermometry Task Group for Emerging Technologies (BIPM CCT TG- CTh- ET) and BIPM Consultative Committee for Acoustics, Ultrasound and Vibration (CCAUV), the NEN Committee on Interconnection of information technology equipment, DKD Technical Committee on Force and Acceleration, CEN TC 264 Air quality and IEC SC65B on Measurement and control devices.

Longer-term economic, social and environmental impacts

A recent Accenture study highlighted a potential reduction in costs and improvement in resource efficiency of up to 90 % and approx. 30 %. growth in productivity due to the future implementation of the IIoT, The outcomes from this project will support this implementation and foster the long-term development of a metrological infrastructure for the digital age by providing ready-to-use templates for the dynamic calibration of digital sensors and validated data analysis procedures for the IIoT. Moreover, sensor networks are widely used in weather prediction and for monitoring environmental conditions such as air pollution and water quality. Hence, they are subject to the same problems addressed in this project and the methods we have developed could bring long term benefits to these sectors too.

List of publications

1. "Primary calibration of mechanical sensors with digital output for dynamic applications" Seeger, B. and Thomas, B., Acta IMEKO 10 (2021), 177 – 184 http://dx.doi.org/10.21014/acta_imeko.v10i3.1075

2. “Influence of synchronization within a sensor network on machine learning results” Dorst, T., Robin, Y., Eichstädt, S., Schütze, A. and Schneider, T., Journal of Sensors and Sensor Systems 10 (2021), 233-245 https://doi.org/10.5194/jsss-10-233-2021
3. “E2.3 Propagation of uncertainty for an Adaptive Linear Approximation algorithm” Dorst, T. and Eichsädt, S., AMA SMSI 2020 E2 Future (2020), 366 – 367 https://doi.org/10.5162/SMSI2020/E2.3
4. “E3.4 Calibration of Digital Dynamic Pressure Sensors” Yilmaz, R., Durgut, Y. and Hamarat, A., SMSI 2020 Conference – Sensor and Measurement Science International SMSI 2020 (2020), 376-377 https://doi.org/10.5162/SMSI2020/E3.4
5. “Toward smart traceability for digital sensors and the industrial Internet of Things” Eichstädt, S., Gruber, M., Vedurmudi, A. P., Seeger, B., Bruns, Th. and Kok, G. MDPI Sensors, 21/6), 2021 https://doi.org/10.3390/s21062019
6. “D1.1 GUM2ALA – Uncertainty propagation algorithm for the Adaptive Linear Approximation according to the GUM” Dorst, T., Schneider, T., Schütze, A. and Eichstädt, S. SMSI 2021 Conference – Sensor and Measurement Science International SMSI 2021, 314-315 https://doi.org/10.5162/SMSI2021/D1.1
7. “Optimization of sensor distribution using Gaussian Processes” A. Forbes, K Jagan, J Donlevy, J Alves e Sousa, Measurement: Sensors/Acta IMEKO 18 (2021), 100128, https://doi.org/10.1016/j.measen.2021.100128
8. “Metrology for the Factory of the Future” Eichstädt, S. "Research Outreach (2021) DOI: 10.32907/RO-126-1869538673

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>June 2018, 40 months</td></tr>
<tr><td colspan="3">Coordinator: Sascha Eichstädt, PTB Tel: +49 30 3481 2008 E-mail: sascha.eichstaedt@ptb.de
Project website address: https://www.ptb.de/empir2018/met4fof/home/</td></tr>
<tr><td>Internal Funded Partners:
1 PTB, Germany
2 CEM, Spain
3 IMBiH, Bosnia and Herzegovina
4 INRIM, Italy
5 IPQ, Portugal
6 LNE, France
7 NPL, United Kingdom
8 TUBITAK, Turkey
9 VSL, Netherlands</td><td>External Funded Partners:
10 SPEA, Italy
11 STRATH, United Kingdom
12 TU-IL, Germany
13 UCAM, United Kingdom
14 ZEMA, Germany</td><td>Unfunded Partners:
15 ITRI, Taiwan</td></tr>
<tr><td colspan="3">RMG1: IMBiH, Bosnia and Herzegovina (Employing organisation); PTB, Germany (Guestworking organisation)</td></tr>
<tr><td colspan="3">RMG2: IMBiH, Bosnia and Herzegovina (Employing organisation); PTB, Germany (Guestworking organisation)</td></tr>
</table>