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 will establish a metrological framework for the complete lifecycle of measured data in industrial applications: from calibration capabilities for individual sensors with digital pre-processed output to uncertainty quantification associated with machine learning (ML) in industrial sensor networks. Implementation in realistic testbeds will demonstrate the practical applicability and provide templates for 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 recent surveys, one of the top priority industrial needs in the FoF is data quality. This project addresses the need for data quality interpreted as the need for a measurement uncertainty framework supporting a metrological infrastructure. In order to address the complete flow of information this infrastructure has to cover traceable calibration of smart sensors taking into account dynamic effects, metrological treatment of complex sensor networks and uncertainty evaluation for the data aggregation and decision-making methods. Previous projects 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 calibration facilities need to be extended to digital-only sensors, which requires 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 needed to associate their output with reliable uncertainties. Methodologies for sensor network metrology also need to be extended and real-time ML methods need to be developed to address uncertainty evaluation in industrial sensor networks.

Objectives

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

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.

The project also focuses on two very common challenges in manufacturing; (i) process optimisation and (ii) predictive maintenance; represented by three specific testbeds using 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, will be considered consistently.

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 will provide digital-only time-dependent output and will have internal signal processing capabilities. This makes 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 kind of “smart sensors” with digital output and/or with internal pre-processing. Therefore, this project extended NMI-level dynamic calibration facilities to sensors with digital output, internal pre-processing. Therefore, 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. In this way, the measurement uncertainty contribution corresponding to the extension of the existing calibration setup for analogue sensors is relatively small. This concept works as well for digital sensors with sample-by-sample output as for those with batch-wise provision of data. The DAU can also be used outside the calibration setup as a means to integrate digital sensors into a sensor network. The DAU can then provide certain smart features, such as communication of units of measurement in the D-SI format developed in IND02 SmartCom or a reference to a digital calibration certificate (DCC). Together with the agent framework for the efficient implementation of sensor network data analysis, the digital acquisition unit can be combined to 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, in order to incorporate their information into a quality-ensured FoF, reliable calibration information is required. Before this project there was a lack of a corresponding metrological infrastructure that meets the needs of industrial stakeholders as well as metrological requirements for traceability to SI. Therefore, this project developed and validating a first automated testbed equipment 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. A so-called reference fixture, which contains several reference sensors, is calibrated in a laboratory traceable to the SI. This fixture is then used to provide traceable batch calibration of MEMS sensors, by mounting the fixture on the ATE machine. The setup is validated and further optimised based on simulation analyses.

Metrology for industrial sensor networks

Metrological frameworks for sensor networks are currently at a comparatively early stage of development, with previous projects e.g. EMRP ENG63 only beginning to address the challenge. However, decisions in the FoF are based on measurements from a diverse network of sensors. Therefore, these measurements are 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 is extending sensor network metrology in order to deal with network communication issues to FoF environments, taking specific requirements such as sensor capabilities and real-time data analysis and decision-making into account. To do this, the outcomes of the calibration framework for digital sensors are combined into networks of sensors. The project outlined generic modelling approaches taking sensor models, timing issues, synchronisation and redundancy into account. Mathematical-statistical methods for the mitigation of jitter and other timing issues have been developed.

In particular redundancy in a network can be utilized in a sensor network, if known. The project reviewed existing methods from the literature, focusing on those that take uncertainties into account. Based on these methods, data from the project's testbeds was analysed considering the dependence of uncertainty on the removal of sensors.

FoF testbed implementations

This project is extending three existing industry-like testbeds that have been developed and validated in previous industry projects to a metrological framework for digital sensors and ML for sensor network analysis: (1) the SPEA automated test equipment for MEMS temperature calibration 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. Moreover, selected data sets generated by these testbeds will be made available to foster development of ML in metrology. Testbeds (2) and (3) are equipped with the "Smart Traceability" prototypes. Testbed (1) is extended with the development of a reference fixture for MEMS batch calibration.

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 has developed the required 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 board to upstream systems. These are running the agent-based framework (ABF) developed within the project to enable easy integration with data analysis method developments. The ABF in turn, is capable of providing the measurement information in arbitrary protocols. For example, the OPC-Unified Architecture was implemented, which provides data streams from the board to connected PCs. For the communication of the data from the µC board, a collaboration with the EMPIR project 17IND02 SmartCom has been carried out to integrate the D-SI data model into the ABF. The software corresponding to the µC board and the adaption to the agent-based framework has been published on the project's open source repository on GitHub (https://github.com/Met4FoF).

A first application of the new hardware was a dynamic calibration concept as an extension to the existing acceleration calibration facilities at PTB. As part of this, the µC board provides an additional ADC channel which samples (and timestamps) a dedicated synchronisation signal in parallel to the DUT's digital output. First prototypical phase response measurements were successfully performed with this extension. This extension is also integrated at the calibration facilities at CEM. A second application of the new hardware is the integration of calibrated MEMS sensors for temperature and acceleration into the testbeds at ZEMA and STRATH. In this way, the two testbeds are extended with calibrated data for further data analyses and insights.

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 started development of a proof-of-concept “Smart Traceability” sensor by extending a conventional sensor with a “Smart-up Unit”, such that it provides measured values together with their associated uncertainty and other relevant data quality information. Furthermore, the project further developed the software from EMPIR project 14SIP08 by extending the corresponding software library PyDynamic. The existing PyDynamic software library was extended to 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. In addition, the development of modules for reading and writing digital calibration certificates has been started in collaboration with 17IND02 SmartCom and the joint Stakeholder Advisory Board (SAB) for the projects.

The testbed at ZeMA was equipped with digital-only sensors for acceleration and temperature calibrated at PTB and INRIM with support from SPEA. The sensors provide their data via the µC board to the data acquisition unit system. This installation is carried out in the same way for the testbed at STRATH. Both testbeds are then able to produce new data sets including reliable uncertainty statements.

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 an automated testbed equipment (ATE) at the SPEA testbed for traceable in-situ calibration of MEMS temperature sensors using a network of reference sensors in an automated test environment. The initial design of the ATE setup has been implemented and the laboratory calibration facility for the traceable calibration of the on-board temperature sensors of the reference fixture has been finished. First data analysis and simulations have been carried out and are used to further optimise this novel calibration setup. The setup uses on-board temperature sensors to generate a temperature mapping for the calibration of the MEMS sensors.

Objective 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.

Generic mathematical models have been derived and several uncertainty evaluation approaches have been implemented. In particular, typical methods for feature extraction methods as the first step in ML have been extended with uncertainty propagation. Several approaches for the assessment and exploitation of redundancy in sensor networks have been identified and applied to testbed data sets. Based on models of the data collected by digital sensors (subject to noise and jitter effects), methods have been developed to account for timing and synchronisation issues. With the implementation of these methods in an ABF, the flexible use of a variety of sensor networks can be achieved. The ABF 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. In order to bring metrology into this area, the uncertainty associated with the raw data streams has to be taken into account by the ML methods applied. As a first step, the methods already in use for the STRATH and ZEMA testbed data were investigated regarding their extension to take into account measurement uncertainties. In addition, probabilistic ML methods are being evaluated with the data sets so far provided by the project’s testbeds. In order to increase early up-take of these developments, initial data sets have been made publicly available on the Zenodo repository under a dedicated Met4FoF community page (https://zenodo.org/communities/met4fof/. In addition, the development of web-based tutorial for using the data sets has been started. A first version of a tutorial webinar on the ABF system and one for the application of ML to the ZeMA data set have been recorded and uploaded on the project website. Web-based tutorials on the available data sets have been integrated with the project’s GitHub repository and three data sets have been published with open access: STRATH data set, ZeMA data set of one cylinder, ZeMA data set with three cylinders. The data sets will be updated and combined with further web-based tutorials on their application with Python-based ML taking into account measurement uncertainties.

Impact

This project has formed a joint stakeholder advisory board (SAB) together with the project 17IND02 SmartCom. The SAB so far includes 10 partners from industry, academia and standardisation, who have helped to decide on the most suitable sensors and interfaces for the project. Moreover, 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. At invited presentations at the "19th International Metrology Congress", "MathMet Conference 2019" and at the "Dresdner Sensorsymposium" the project has also been disseminated to a wide community in science and industry.

In order to increase the uptake of the mathematical methods developed in the project, a public GitHub repository has been launched (https://github.com/Met4FoF). This repository connects all software developments from the project and employs modern software quality principles with CI technologies. All partners who write software code are regularly adding to this repository. The joint repository is set up such that the individual repositories of the partners can be organised separately and was recently presented at the German conference "deRSE19 - Conference for Research Software Engineers in Germany" in June 2019.

Impact on industrial and other user communities

This project will impact industries that use sensor networks, in particular those using digital sensors for monitoring mechanical quantities such as acceleration, force and pressure. It 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 provision of measurement capabilities with internal pre-processing. The concepts and proof-of-principle "Smart Traceability" sensors that are 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 into the post-processing data element of a "Smart Sensor". In order to support this impact, all software written by the project for the smart-up unit is 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 is transferred into a commercial calibration service to support industrial end-user use. Moreover, the calibration framework for temperature measurements 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, the project's SAB includes the Institute for Systems and Computer Engineering, Technology and Science (INESC) as an expert in MEMS sensors.

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 support a reliable uncertainty assessment together the methods' results. Moreover, data management will be simplified with in-situ sensor identification and sensor data communication, e.g. the measurement data communicated from smart-up units to connected PCs is combined by this project with PyDynamic routines adapted to work in a data streaming environment.

With the combination of metrology for digital sensors, industrial sensor networks and the respective data analysis, the whole traceability chain will become digitally enabled. Practical demonstrations of the approaches are shown by implementation in industrial testbeds. Therefore, this project and the project 17IND02 SmartCom have started the development of a demonstrator based on the smart-up unit, the SmartCom digital communication guidelines and the Met4FoF data analysis methods.

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. The nationally funded projects will implement several developments from this project 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. Hybrid networks involving both low-quality and reference sensors, though, may well outperform a network of low-quality sensors. An important design aspect is to match the aggregate sensing capability with the complexity of the underlying system, i.e. stable, predictable systems need less measurements while complex, evolving systems need more measurements. The results of this project on the balancing of costs versus quality by considering measurement uncertainty throughout the data lifecycle can help to increase the uptake of metrological principles in such networks. Moreover, the methods developed for the calibration of MEMS sensors will provide new approaches for the cost-efficient application of traceable in-situ calibration for low-cost sensors. The project partners have already used the smart-up unit as a basis for a simple implementation of MEMS sensors in the project's testbeds.

ML development relies on the availability of realistic and well-documented data. Therefore, test data sets from the testbeds used in this project are made available to foster further developments for uncertainty evaluation in ML. Guidelines, training courses and best-practice guides will also be produced to increase the application of ML in metrology. On a European level, the European Centre for Mathematics and Statistics in Metrology (MATHMET) will provide a means of engaging with a range of user communities in the industrial sector as well as in mathematics and statistics. Together with collaborators from its SAB the project will contribute to the software quality frameworks in EURAMET's European Metrology Network MATHMET.

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. The project will promote the results of the metrological framework for digital sensors within the standardisation community and provide input to relevant standardisation groups, such as ISO/TC 108 WG34 dealing with acceleration, force and pressure.

Project partners involved in relevant standardisation bodies such as Department 1 of the Society for Measurement and Automation Technology of the Association of German Engineers (VDI/VDE-GMA 1), DIN Standards Committee Acoustics, Noise Control and Vibration Engineering Standards (NALS), BIPM Joint Committee for Guides in Metrology (JCGM) working group 1, Association for Sensors and Measurement (AMA) WG "Industry 4.0", IMEKO TC 21, BIPM Consultative Committee for Thermometry Task Group for Emerging Technologies (BIPM CCT TG-CTh-ET) and IEC SC65B WG 5 will inform these groups about the project. For example, the project was presented at a meeting of the DKD working group "Acceleration" of the technical committee "Force and Acceleration". Moreover, liaisons with organisations such as NEN have been started with relevant working groups.

Longer-term economic, social and environmental impacts

Through the comprehensive implementation of IIoT, an Accenture study highlights the potential for cost reductions and improvements in resource efficiency of up to 90 % with growth in productivity estimated to be about 30 %. This project will foster the development of a metrological infrastructure for the digital age by providing ready-to-use templates for dynamic calibration of digital sensors and validated data analysis procedures for IIoT. Moreover, sensor networks are widely used in weather prediction and for monitoring environmental conditions such as air pollution and water quality and are subject to the same problems addressed in this project and the methods developed in this project will be disseminated to these sectors.

List of publications

Not yet available

This list will also be 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, 36 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>
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<tr><td colspan="3">RMG2: IMBiH, Bosnia and Herzegovina (Employing organisation); PTB, Germany (Guestworking organisation)</td></tr>
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