17IND12 Met4FoF

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 instance, in EMRP 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 will extending the dynamic calibration facilities developed in EMRP IND09 to sensors with digital output, internal pre-processing and with targeted measurement uncertainty similar to the analogue measurement”. The project will also develop the required basic concepts, terminology and specifications as well as a proof-of-concept “Smart Traceability” sensor.

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 will develop and validate an 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.

Metrology for industrial sensor networks

Metrological frameworks for sensor networks are currently at a comparatively early stage of development, with previous projects such as EMRP ENG63 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 will extend 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 will be combined into networks for aggregated or distributed measurements. Using redundant information in the network, new concepts such as co-calibration of sensors and extrapolation of calibration information from individual sensors to others of the same type will be addressed. Efficient implementation will be achieved by using a so-called agent-based software framework.

FoF testbed implementations

This project will extend at least 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.

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 so far developed the required basic concepts, terminology and specifications. As a first step, the project developed a micro-controller (µC) board that can hold digital sensors and provides time-stamping traceable to SI. A communication interface based on OPC-Unified Architecture provides data streams from the board to connected PCs and will later be used for the implementation in the project's testbeds. For the communication of the data from the µC board a collaboration with EMPIR 17IND02 SmartCom has been initiated to develop a joint demonstrator. The software corresponding to the µC board was published on the project's open source repository on GitHub (https://github.com/Met4FoF).

For the extension of the ZEMA and STRATH testbed, the prototype "Smart-up Unit" is being prepared to integrate MEMS sensors measuring temperature, pressure and acceleration. Collaboration with 17IND02 and the joint Stakeholder Advisory Board (SAB) on the integration of digital communication and digital calibration certificates has been initiated.

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

This 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 initiated further development of the software implementations from EMPIR 14SIP08 by extending the corresponding software library PyDynamic. As an initial step, the existing PyDynamic repository 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 the project to an implementation of the mathematical framework developed in the project. In addition, in collaboration with EMPIR 17IND02 SmartCom and the joint SAB the development of modules for reading and writing digital calibration certificates has been started.

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 begun the development of an 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. The initial design of the ATE setup has been drafted and development of the corresponding parts has started. The laboratory calibration facility for the traceable calibration of the on-board temperature sensors of the reference fixture is under construction and an initial version will soon be finished. Data analysis methods will be developed in this project for this novel calibration setup that 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 potential uncertainty evaluation approaches have been identified. Based on these models, methods are being developed for the transformation of timing and synchronisation issues and use of redundant information. With their implementation in an agent-based framework (ABF), the flexible use of a variety of sensor networks will be achieved. The basic outline of the ABF has been created and its implementation started. In a first step the ABF will then be used to simulate a heterogenous sensor network.

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 an initial step, the methods already in use for the STRATH and ZEMA testbed data are being 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, development of web-based tutorial material for using the data sets has been started. The data sets will be updated with further information and combined with further web-based tutorials on their application with Python-based ML taking into account measurement uncertainties. In addition, it is intended that software releases from the project will be published on the Zenodo platform with an associated persistent identifier as DOI.

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. With support from the SAB the project decided on the sensors and interfaces to be considered in the project. Moreover, together with SAB members the project is preparing a joint publication for the 2019 IMEKO TC10 conference, developing the design and implementation of the smart-up unit and outlining the development of the agent-based software framework.

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 continuous integration (CI) technologies. All partners who write software code are regularly adding to this repository. The joint repository is set up in a way such that the individual repositories of the partners can be organised separately. This setup will be presented at a 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 apply sensor networks, with early impact in particular for industries using digital sensors for monitoring mechanical quantities such as acceleration, force and pressure. Existing NMI calibration facilities for dynamic calibration of mechanical quantities will be extended to deal with digital-only sensors. This will provide 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 will be developed in this project are easily applicable to other sensor types and data post-processing tasks. Thus, these concepts will serve as templates for NMIs and sensor manufacturers and is expected to stimulate new ways of collaboration. For instance, a metrological service could be offered by NMIs to sensor manufacturers or could support the implementation of the calibration information and measurement uncertainty evaluation into the data post-processing element of a "Smart Sensor". In order to support this development, all software written for the smart-up unit will be made available as open source by the project on the public GitHub repository mentioned above.

Due to their cost-efficiency and versatility, MEMS are increasingly employed in the IIoT. The in-situ calibration framework for MEMS temperature sensors developed in this project will be transferred into a commercial calibration service to support industrial end-users. 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 dependence on temperature and humidity. To support this, the project's SAB includes INESC as an expert in MEMS sensors to guide the development of the one-touch calibration setup.

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 to be developed and validated in this project will support a reliable, real-time uncertainty assessment. Moreover, data management will be simplified with in-situ sensor identification and sensor data communication. In a first step the measurement data communicated from smart-up units to connected PCs will be combined by this project with *PyDynamic* routines adapted to work in a data streaming environment. In a next step, these methods will be integrated in the agent-based framework for a versatile implementation in flexible sensor networks.

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 usefulness of the approaches will be demonstrated by implementation in industrial testbeds to increase the uptake by industrial end-users. Moreover, a SAB has been established to exchange information regularly within this project and with the project 17IND02 SmartCom. Both projects are planning to develop a joint mobile 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 a nationally funded research project in Germany to combine metrology for sensor networks with asset administration shell approaches, standardised as "RAMI4.0". This nationally funded project starts in June 2019, is coordinated by the Fraunhofer institute for open communication systems (FOKUS) and includes collaborators from academia and industry. The nationally funded project will run for three years and will implement several developments from this project Met4FoF in additional industrial testbeds. In order to foster the cooperation between the two projects, the inclusion of Fraunhofer FOKUS in the SAB is currently on-going.

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, for instance, in terms of information gain per unit cost (of supply and maintenance). 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 will increase the uptake of metrological principles in such networks. Moreover, the methods developed for 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 will use the smart-up unit as basis for a simple implementation of MEMS sensors in the testbeds considered in this project. In a similar way, other laboratories and testbeds could be extended in the future.

ML development relies on the availability of realistic and well-documented data. To this end, test data sets from the testbeds used in this project will be made available to foster further development of methodologies for uncertainty evaluation in ML. Guidelines, training courses and best-practice guides will 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. Several projects partners are contributing to the 2019 MATHMET workshop in a dedicated session. Together with collaborators from the SAB the project will also contribute to the EMN MATHMET activities on software quality frameworks.

Impact on relevant standards

Existing standards for calibration of sensors, like the ISO 16063 series for the calibration of vibration and shock sensors, need to be revised in order to account for digital output data streams. New requirements must be defined, the terminology adapted, and new approaches established to deal with digitally pre-processed output data. 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 dealing with acceleration, force and pressure.

Project partners who are involved in corresponding standardisation bodies and committees such as DKD have informed these groups about the project's existence and goals. For instance, the project aims have been 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 initiated by reporting the project aims and research plan to the related 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. In the medium term, the methods developed in this project will be disseminated to these sectors.

<table>
<tr><td colspan="2">Project start date and duration:</td><td>June 2018, 36 months</td></tr>
<tr><td colspan="3">Coordinator:
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<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>
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