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 Met4FoF project comprises the following main objectives:

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

- 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.
- 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.
- 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 technical work also focuses on two very common challenges in manufacturing – process optimisation and predictive maintenance – represented by three specific testbeds using different types of sensor networks.

1. 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.
2. 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.
3. 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 and expected results

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. 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 will result in a metrological framework and infrastructure for the increasingly relevant field of so-called “smart sensors”. The project will develop the required basic concepts, terminology and specifications as well as a proof of concept by calibration of a selected group of digital interface sensors. Similarly, the project will further develop the software implementations from EMPIR 14SIP08 by extending the corresponding software library *PyDynamic*. In addition, this project will develop a proof-of-concept “Smart Traceability” sensor by extending a conventional sensor, such that it provides measured values together with their associated uncertainty and other relevant data quality information.

In many Industrial Internet of Things (IIoT) environments, MEMS are applied 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. 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 at a comparatively early stage of development, with previous projects such as EMRP ENG63 beginning to address the challenge. On the other hand, decisions in the FoF are based on measurements from a diverse network of sensors. 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 this end, 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.

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. Therefore, this project will investigate and further develop existing ML methods to lay the foundation for metrology in ML.

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.

Impact

Impact on industrial and other user communities

This project will impact all 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. Examples are monitoring of vibration, temperature and hydraulic pressure in the forming of materials or in precision positioning for high-value manufacturing.

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”.

Due to their cost-efficiency and versatility, MEMS are increasingly employed in the IIoT. For instance, the technology analyst company IHS predicts a total of 7.3 billion MEMS devices in the IIoT by 2025, in particular for temperature and humidity monitoring. 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.

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. 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.

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. These testbeds will also be used to carry out training courses for industrial end-users. Moreover, a stakeholder advisory group will be established and will exchange information regularly with the project to advise and stimulate the developments. Where relevant, exchange with other projects will be carried out in such a way to foster synergies and identify joint activities.

Impact on the metrology and scientific communities

The demonstration of existing NMI calibration facilities to become digitally-ready and the lessons learned will be provided as best-practice guidance to standardisation bodies and to support the uptake of these developments by other metrology and calibration institutes.

In the future, calibration of smart sensors will contain a “calibration” (possibly in the sense of validation) of the sensor’s internal data pre-processing. The development of sensor concepts with built-in “Smart Traceability” in this project will lay the foundation for a new understanding of data analysis in the application of sensors.

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.

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.

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.

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.

Project start date and duration:	June 2018, 36 months	
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