A smart sensor Concept for traceable dynamic measurements

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Abstract. Smart sensors are the metrological challenge of the current trend towards digitization and “Internet of Things” (IoT). In particular for use in dynamic measurement applications, these cross-linked devices could help to provide more accurate and reliable data for the user while at the same time relieving the burden of complex signal processing. This paper presents a concept for a smart sensor in metrological terms. It is a forecast of the development that is to be implemented in an approved joint European research project which is about to start in the summer of 2018.

1. Motivation
Traceable dynamic measurements with reliably estimated measurement uncertainties pose a great challenge in many applications and to many users. Although there have been many efforts to provide the metrology tools and facilities to overcome the various problems, the sometimes complex interaction of a measurement object and a measurement system may lead to mathematical descriptions and models which are difficult for engineers to implement and validate.

But imagine a situation where the measurement system “knows” about the interaction and “knows” about its own internal properties and states. And imagine a measurement system that has the capability to join that knowledge with the measured data of its sensor element to a set of augmented information. For such a system, based on the metrology community’s achievements of recent years, it would be possible not only to provide a raw measurement value, but also a corrected value taking into account the known influences of interaction and transmission and an associated measurement uncertainty based on the current state of the system (time-dependent). The current state is an important issue in dynamic measurements, and in cases where more than one sensor is involved in a measurement task, synchronization is a mandatory feature of the system. Considering measurands with frequency contents in the acoustical range (< 20 kHz) and phase-delay requirements in the order of a few degrees, the timing or synchronization requirements for different channels are in the order of 1 µs or less. Such conditions are not easy to comply with using off-the-shelf networking hardware.

In addition to these strictly measurement-related data, complementary information about the sensor state such as calibration data, the due date of the next calibration, the maximum load borne, the number of load cycles, etc. could be provided to the user.
The result would be a sensor with what we call smart traceability, meaning, a smart sensor in the metrological sense.

2. Prototyping

2.1. Hardware

In order to gain maximum control for the development of a smart sensor for dynamic measurements, a modular approach with openly accessible hardware and software will be adopted. An independent non-smart sensor module with digital (or even analogue) output will be linked to a network-capable processing unit. Together they act as the smart sensor module. While the sensor module acquires the raw measurement data, the processing unit has multiple tasks to fulfil:

1) to receive accurate time information over the network,
2) to acquire the raw measurement data from the sensor,
3) to bind measurement data and time information forming an information sample,
4) to calculate auxiliary measurement-related results (correction, uncertainty),
5) to handle requests from network clients in order to deliver measurement data or other information,

... Some of these tasks are quite critical concerning their timing, like 2) and 3), and may be delegated to an FPGA module, others are more appropriately solved in a high-level programming language like Python or Java, facilitating established software libraries and services in the environment of a suitable operation system. Figure 1 depicts a schematic representation of the concept. Accordingly, the processing unit needs to provide different architectural sections in itself. Compact designs that appear to comply with these requirements are, for example, STEMlab’s redpitaya® or National Instruments’ myRIO®.

2.2. Software

As already suggested in the section above, the whole smart sensor system will involve parts with critical timing requirements and other parts which are not so critical but are more elaborate in terms of protocol and networking. Accordingly, the software which is to be implemented and the tools used for the development will be designed and chosen according to the needs.

The parts with critical timing include the sampling of raw data, the linking to sample time stamps, the application of digital filters and/or corrections, and the calculation and assignment of the current measurement uncertainty. In addition, internal state variables may be updated with each new sample. It is planned to implement these tasks in a main loop structure within an FPGA core. This approach will guarantee a strictly hardware-determined scheduling for each

1 FPGA=field programmable gate array
subtask and thus, a fixed time consumption for each turn of the loop. The implementation has to be realized using hardware description languages like VHDL or Verilog.

The system parts comprising the network interaction and the distribution of the measurement data will be implemented in the environment of a conventional operation system (OS) preferably using an open source kernel. This has the benefit of providing ready-to-use software libraries for the basic network functions and protocols. High-level languages like C, C++, Python, etc. are readily available and not only the metrological algorithms, but even their implementations from prior dynamic metrology developments, e.g. [1], [2], can be transferred directly.

2.3. Network and protocols
With respect to the network interaction and data distribution, different requirements have to be satisfied. The measurement data, whose acquisition is the primary task of a sensor, have to be distributed in a continuous stream with low latency in order to be useful for typical monitoring or control applications. This could be accomplished by using websocket connections or one of the established streaming protocols used, for example, for internet audio or video streaming. Calibration data or information about the internal state are more single request events, but may be useful in a machine-readable as well as a human-readable format. For that reason, a solution using XML, XSLT, HTML and a webserver appears to be more appropriate. A different project currently running at the Physikalisch-Technische Bundesanstalt (PTB), which is developing a standardized digital calibration certificate using XML schemata [3], may deliver an important contribution in this field of work.

3. Data features
3.1. System response correction (deconvolution)
As already pointed out in the introduction, dynamic measurements pose a special challenge to metrology owing to the frequency-dependent response of the sensor system (and possibly of parts of the structure it is mounted onto, as well), c.f. [4]. The smart sensor concept provides the opportunity of shifting the task of correction for those dynamic influences from a user-related post-processing exercise (today) to a sensor-related real-time task performed in the smart sensor (in the future). However, this requires the real-time capability of the implemented algorithms, which is not yet available in all cases.

From a metrology standpoint, there are two primary operations that have to be performed on the measured data:

1) the elimination of the frequency response of the measurement chain by deconvolution and band limitation based on dynamic calibration results,

2) the calculation of the measurement uncertainty based on a validated dynamic model of the system.

An example of how to deal with such operations for real-time applications is given in [5] or [6]. The distribution of both time series of measurand and associated uncertainty doubles the number of channels in comparison to conventional sensors. However, in analogy to audio transmission, this is like the move from mono to stereo systems. Transmission protocols are readily available for such tasks.

3.2. Calibration information
In large multi-sensor measurement setups, it is crucial to have automatic sensor identification and automated access to information related to individual sensor properties. A first approach to find a standardized solution for this issue was [7], where an interface for analogue sensors is described that enables the identification of the sensor and a read-out of sensitivity data by using dedicated measuring amplifiers with embedded special electronics.
Using standard network technology, the options of providing and accessing such information become much more flexible. Based on the work of a project currently running at PTB [3], a complete digital calibration certificate will be deliverable by the smart sensor system. Such a data set includes all traceability information available for the individual sensor. This includes among other (mainly administrative) information:

- date of calibration,
- laboratory of calibration,
- calibration results (like tabulated complex frequency response),
- expanded measurement uncertainty,
- unit of measurement (SI related),
- coverage factor,
- environmental conditions during calibration.

The calibration information, which is stored in a standard XML schema, can be provided in both, a machine-readable and a human-readable format. It is also possible to consider a direct network-based update of this calibration information. However, this may raise questions of data security.

4. Summary

A future European collaboration project will, among other things, develop and implement a sensor concept that is smart in metrological terms. The focus for this development will be the augmentation of an IoT-capable sensor to provide not only pure measurement data, but also data that take into account the sensor’s transfer characteristics, that provide reliable measurement uncertainty and time data for dynamic measurements, and that delivers upon request all necessary information regarding the traceability status.

At the same time, the concept involves algorithms programmed close to machine level as well as abstracted network service programming. It will be realized in a modular approach, both in software and in hardware.

This concept also sets out novel services for metrology institutes and calibration laboratories, such as the development of methodologies for smart traceability in order to increase confidence in data quality for the IoT era.

References

[1] Eichstädt S and Wilkens V 2016 Measurement Science and Technology 27 055001 URL http://stacks.iop.org/0957-0233/27/i=5/a=055001
[2] Bruns T and Volkers H 2017 Proc. of the IMEKO 23rd TC3, 13th TC5 and 4th TC22 International Conference (Helsinki, Finland: IMEKO) URL http://www.imeko.org/publications/tc22-2017/IMEKO-TC22-2017-007.pdf
[3] Hackel S, Härting F, Hornig J and Wiedenhöfer T 2017 PTB Mitteilungen 127 75 URL https://www.ptb.de/cms/presseaktuelles/zeitsschriften-magazine/ptb-mitteilungen.html
[4] Kobusch M and Eichstädt S 2017 Acta IMEKO 6 3–12 URL http://dx.doi.org/10.21014/acta_imeko.v6i1.433
[5] Elster C, Eichstädt S and Link A 2010 Sensors 10 7621–7631 URL http://dx.doi.org/10.3390/s100807621
[6] Link A and Elster C 2009 Measurement Science and Technology 20 055104 URL http://stacks.iop.org/0957-0233/20/i=5/a=055104
[7] TMC - Transducer to Microprocessor Communication Working Group 2004 IEEE 1451.4 standards series URL https://standards.ieee.org/findstds/standard/1451.4-2004.html