FUNDAMENTAL ASPECTS OF METROLOGICAL SUPPORT IN IoT

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Abstract. The application of intelligent sensors, network technologies, and machine learning in IoT and industry is increasingly widespread as a part of the development and implementation of Industry 4.0, Industry 5.0, and Smart City. It is necessary to review the fundamental principles of metrological support for production. This includes calibration, estimation of measurement uncertainty, traceability, and processing of large data sets to reproduce and compare the results of measurements of physical quantities remotely. Modern smart sensors are cost-effective, which makes traditional sensor calibration methods increasingly uneconomical. The utilization of advanced networking technologies, along with machine learning, complicates the pre-processing of measured values. Therefore, new solutions are required when it comes to implementing digital metrology.

In this article, a metrological framework for the full life cycle of measured data in IoT is presented. It ensures transparency, comparability, consistent quality and reliability of measured data, processing methods and results. The OPC-UA digital data communication standard is considered, which provides a single interface for exchanging digital data with devices from different manufacturers or via different protocols. The syntax of a machine-readable representation of SI units and derived quantities as well as the structure of the sensor network metadata model are also described. Special emphasis is placed on dynamic calibration of sensors, determining measurement uncertainty in sensor networks, and implementing digital calibration certificates in IoT and industry.

Key words: Sensor network, measurement uncertainty, Internet of Things, digital calibration.

1. Introduction

Industry 4.0 and IoT require the integration of software, communication, and algorithms into products, processes, and services. Digital data communication is becoming the standard, and information is provided through cloud services. IoT infrastructures utilize calibration information, self-diagnostics, and other metadata transmitted by individual measurement devices and their systems. Quality infrastructure processes and services are based on distributed databases and application programming interfaces (APIs).

Consequently, distributed measuring devices and sensor networks have gained more importance than individual measuring devices. The importance of algorithms and software in metrological traceability cannot be overstated. They have a significant impact on the accuracy of measured values. Artificial intelligence, sensor fusion, and virtual measurement tools will soon replace many existing tools and principles. This requires a fundamental revision of established uncertainty assessment methods and measurement algorithms.

2. Drawbacks

Metrological support has an important influence on the infrastructure of quality in the digital age [1]. However, the science of metrology is still primarily focused on individual measuring instruments and sensors.

Collecting data from sensor networks means focusing on combined information from all sensors instead of individual readings. For instance, combining microphone data and vibration measurements during preventive maintenance provides more information about the actual state of the monitored device than separate measurements. From the perspective of calibration results, however, these factors complicate both the determination of the measured value and the assessment of the entire system's reliability. Potential sensor failures, network problems, power consumption, network sensor location, and network communication synchronization must be considered [2].

Focusing on sensor data combination, measurement performance evaluation should treat the sensor network as a complex, often distributed measurement instrument. To process such sensor networks metrologically, a new approach termed “systems metrology” is required. It includes such aspects as in-situ and collaborative calibration, uncertainty estimation for dynamic measurements and dynamically structured systems, semantic representation of metrological information, uncertainty-aware machine learning and artificial intelligence applied to sensor networks. These topics hold great potential for the field of artificial intelligence, although they are still in the early stages of research [3].

Although industrial digitalization is becoming more widespread in the context of Industry 4.0, Industry 5.0, and Smart City, metrology and calibration are slow to adopt digital technologies. For instance, information on measurement quality or calibration details is typically documented in paper format [4]. The reason for this can be the requirements of existing standards and measurement service traditions. Additionally, the systems used by NMIs may lack the necessary tools or support for digital cryptography to securely authenticate the origin and ensure the integrity of electronic documents, such as digital calibration certificates. But the creation and distribution of secure electronic documents is a well-established practice, digital documents can have the same or even higher security level as paper documents. The application of digital metrology can expand opportunities for data reuse, provide new areas of development such as instant traceability from measurement to sampling conditions following global standards, and create markets for high-quality certified data. [5].

3. Goal

The goal of the current article is to study the main aspects of metrology support in IoT and the challenges caused by the introduction of digital metrology in sensor networks.

4. Study of metrological aspects of the IoT application

4.1. Benefits and challenges of digital metrology in IoT

Metrology in the context of the Internet of Things (IoT) provides accurate and reliable measurements that are applied to decision-making. The benefits of implementing digital metrology and calibration in the IoT include:

- Increasing knowledge about the uncertainties of measuring devices and measurement results;
- Data quality indicators are quantified as metadata;
- Traceability of data quality through certification of the origin, integrity and metrological quality of measurement data;
- Cost savings if calibration is a legal obligation due to automatic data processing.
- Optimization of production processes through high-quality sensor data and improvement of calibration processes by on-site calibration or computational models.
- Preventing data fraud [6].

Challenges and problems in this area:

- Decreased accuracy and productivity due to environmental factors or sensor degradation;
- IoT devices utilizing different communication protocols, data formats, or measurement standards;
- Ensuring secure communication, data encryption, and authentication mechanisms;
- Providing timely and accurate data collection, processing, and analysis;
- Optimizing energy consumption while maintaining measurement accuracy and reliability.
- Balancing cost-effectiveness, accuracy, and reliability of measurements, especially for large-scale IoT deployments.
- Ensuring data quality and noise filtering.
- Compliance with relevant metrology standards, regulations and guidelines.

Applying “smart sensors” enables the resolution of these issues, as they perform data preprocessing in addition to measurement. They provide communication through a digital interface, reliable operation in a wide range of conditions, reporting on their performance status on request, detecting inconsistencies and notifying about the general conditions of measurements [7]. However, the integration of pre-processing in smart sensors places new demands on the calibration of measuring devices, since the pre-processing must also be considered during calibration. This problem can be solved by implementing dynamic sensor calibration, which is described below.

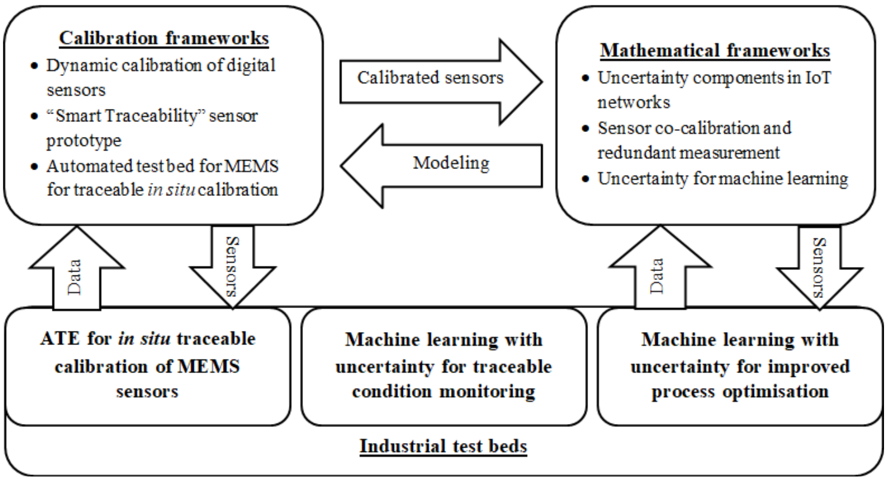


Fig. 1. Metrological framework for the complete life-cycle of measured data

The IoT industry is characterized by autonomous information flow and decision-making. As a result, transparency, comparability, consistent quality, and reliability of measured data, processing methods, and results are crucial requirements [8]. The metrological structure shown in Fig. 1 can be applied to ensure these requirements.

The metrological framework covers the full lifecycle that measured data pass through in industrial applications – from calibration capabilities for individual sensors with digital preprocessing of the output data to quantifying the uncertainty associated with machine learning (ML) in sensor networks.

The key aspect of this structure is the dynamic calibration of a digital output sensor using an external time stamp, e.g., based on GPS and a custom-built microcontroller (μC) board. The main requirement of metrological data processing in a sensor network is the provision of information about the initial measurement values, measurement units, measurement uncertainty, and calibration in a machine-readable way. According to the structure proposed in Fig. 1, this information is provided by the "smart sensor" itself [9-11].

4.2. OPC UA (Unified Architecture) standard

To provide metrological information in a digital format and in a machine-readable way, it is essential to use special standards, one of which is OPC UA (OLE for Process Control with Unified Architecture). A fundamental element of OPC-UA is the concept of sensors providing self-information on demand in a standardized way. [12]. The OPC standard is based on the Windows technologies OLE, ActiveX, COM/DCOM. Its main advantage is a single interface for exchanging data with devices from different manufacturers or using different protocols. Developers of industrial automation devices represent their specific command systems through the universal interface of the OPC server. Any standard OPC client included in any SCADA/HMI/MES/MOM software can read or write data to a standard OPC server. OPC UA is the latest OPC specification to be released, which represents a new level of openness, accessibility, and security. The main advantages of the specification are:

- Cross-platform compatibility, i.e. independence from the operating system. Since OPC UA is not based on Microsoft COM technology, the components support multi-platform implementation;
- Scalability from embedded systems to mainframes;
- Ability to exchange all types of data: real-time, alarms and notifications, history, files;
- Availability of data in a production context, i.e. following the asset model;
- Internal security system.

The OPC UA standard consists of 13 parts (Fig. 2).

To ensure that the metrological information transmitted via OPC-UA is machine-readable, definitions of the standard digital representation of measurement units as well as commonly accepted data models for measurement values must be available. The Digital SI (D-SI) data model is recommended for this purpose. It is compatible with current recommendations and standards in metrology and calibration. [10].

4.3. Digital representation of data and information in IoT

For the digital exchange of metrological data, it is important to associate at least every numerical value with a corresponding unit. This creates a value of a quantity that is interpreted in accordance with the SI units. Due to its indivisibility and fundamental nature, this form of representation is called “atomic representation”.

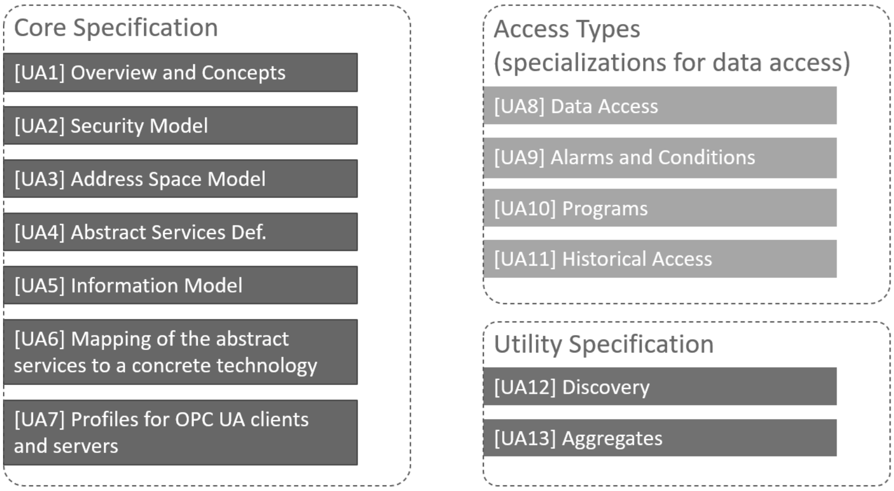


Fig. 2. The composition of the OPC UA standard specifications

The technical realization of SI units in digital formats requires a unique definition of the unit semantics (identifier) and the allowed syntax (combination of identifiers). This necessary machine-readable definition of the SI unit representation is taken from the formal language for units used by Joseph Wright in the Siunitx package. [13]. In addition, it is recommended that a comprehensive set of additional syntax rules from IEC TS 62720 [14] be considered when constructing units in machine-readable SI format.

The syntax for defining SI units is shown in Fig. 3.

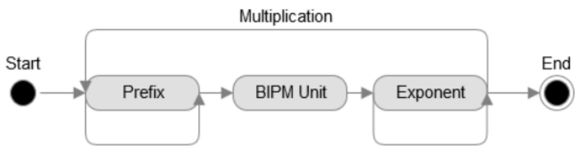


Fig. 3. Syntax for specifying SI unit terms

An important step is to transfer the measured value from a human-readable format to a machine-readable format. Fig. 4(a) shows an example of an XML implementation.

Technical tools need hybrid SI components to work securely with data, but people can still operate with non-SI units. A real quantity in a hybrid consists of a single integer component that must indicate the value of the quantity in the SI unit. It may also provide additional real quantities with derived SI units or non-SI units that are converted to real quantities using the base SI unit. Figure 4(b) presents an example of a hybrid item that utilizes structured XML data.

The user chooses the realization of the data model (XML, JSON or binary file). A reference implementation of the D-SI real value data model is presented in the EMPIR 17IND02 SmartCom project.

The atomic real measured value is the smallest entity for representing a measurement result. Its metadata model structure is shown in Fig. 5(a).

The inclusion of measurement uncertainties in the atomic type of metadata leads to extended formats of real measurement values, as shown in Fig. 5(b).

The metrological data provided by the D-SI data model is classified into different classes of machine readability quality (Table.

According to the table, the quality classes of machine-readable metrological data can be conditionally divided into 5 levels (the “Medal system”), where Platinum is the highest level of data quality, which includes “next generation” data, and Bronze is consequently the lowest. A special class of data is assigned to data that can be improved (Improvable). The Improvable class permits the exchange of measurement data without adhering to the formats described above. This includes reporting values without specifying a unit of measurement, reporting values in a non-decimal numbering system, or separating decimal numbers with a comma or other non-permitted characters. This evaluation system is described in detail in [10].

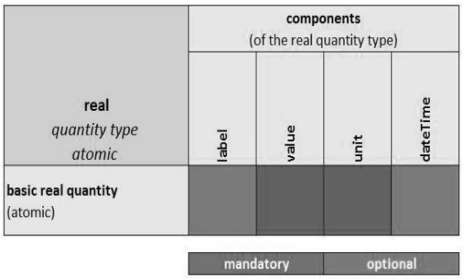
```
<si:real>
  <si:label>temperature</si:label>
  <si:value>20.1/si:value>
  <si:unit>\degreecelsius</si:unit>
  <si:expandedUnc>
    <si:uncertainty>0.5</si:uncertainty>
    <si:coverageFactor>2</si:coverageFactor>
    <si:coverageProbability>0.95</si:coverageProbability>
    <si:distribution>normal</si:distribution>
  </si:expandedUnc>
</si:real>
```

a

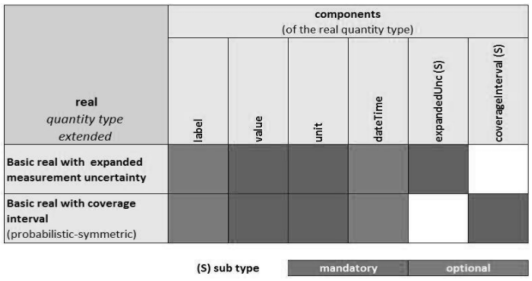
```
<si:hybrid>
   <!-- A: length from B converted to SI -->
   <si:real>
       <si:value>0.3048006</si:value>
       <si:unit>\metre</si:unit>
   </si:real>
   <!-- B: length with imperial unit foot -->
   <si:real>
       <si:value>1</si:value>
       <si:unit>ft(U.S. survey)</si:unit>
   </si:real>
</si:hybrid>
```

b

Fig. 4. XML example for the SI unit (a) and hybrid adapter for real quantities with the unrecommended non-SI unit foot (ft) (b)



a



b

Fig. 5. Metadata models for the atomic specification of real quantity values (a) and for the extension of the atomic quantity value type with measurement uncertainties (b)

Quality classes of machine-readable metrology data

Requirements	Quality class				
	Platinum	Gold	Silver	Bronze	Improvable
SI++ units (7 SI units and 7 important units allowed with the SI)	+	+	+	+	+
SI++ units in hybrid element		+	+	+	+
SI++ units with SI prefix or SI-derived units		+	+	+	+
Non-SI units from the BIPM SI brochure			+	+	+
Units from the previous edition of the SI brochure that are deprecated in the latest edition of the SI				+	+
Unit not part of SI, missing components, wrong data types, …					+

4.4. Dynamic calibration of sensors

The IoT concept is based on a versatile and flexible combination of measuring instruments, automated collection and processing of measured data, and the application of intelligent algorithms to draw conclusions or decisions. Data analysis is performed utilizing data-driven machine learning. As opposed to mathematical models, which rely on a physical understanding of the process being measured, machine learning can be applied directly to the sensor output. Therefore, the necessity for calibration in IoT is not as obvious as in "traditional" measurements. However, calibrated measuring devices in IoT offer several advantages:

- they can serve as reference devices in the network to assess and improve data quality;
- allow to estimate the measured value and, therefore, provide traceability, which is necessary to ensure the comparability of measurements;
- improve the ability to explain the obtained machine learning result.

Calibrated sensors allow for direct interpretation based on the measured quantity, whereas uncalibrated sensors provide data streams that are only weakly related to the physical measured quantity. The manufacturer's specification sheet alone is usually not a sufficient source of information to estimate the Type B uncertaintycomponents. Calibration in the IoT provides benefits at all levels of data processing and increases the level of reliability of the measurement system (Fig. 6).

At the first level (Fig. 6), calibration data is collected from sensor networks of homogeneous and heterogeneous types, as well as from software-based sensors. Calibration data from sensor networks of different types can also be accepted for processing. At the second level, these data are processed and sent to the third level, where a decision about the collected data quality is made based on the processed calibration data.

4.5. Measurement uncertainty in sensor network data processing

Measurement data in sensor networks are heterogeneous, variable, and time-dependent. Low-cost sensing devices based on MEMS technology have a wide range of measurement data quality. Data quality in sensor networks is affected by unstable network conditions, environmental factors, malicious attacks, power consumption-performance relationships, and drift. Therefore, it is necessary to quantify the data quality. It is important to consider sensor characteristics such as effective bandwidth, internal analog-to-digital conversion, timestamp reliability, and resonant behavior.

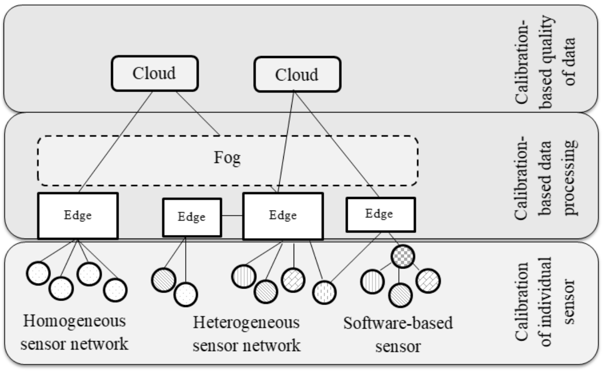


Fig. 6. Calibration information in the different layers of the IoT architecture

Measurement uncertainty is a fundamental property that is an indicator of data quality. The complexity of sensor networks and the large amount of data received require the implementation of machine learning methods to analyze the data and determine the measurement uncertainty. However, without available input uncertainty values, machine learning methods cannot be implemented. Uncertainty for data preprocessing is therefore the initial step towards uncertainty-aware machine learning for the entire sensor network in IoT.

IoT measurements are typically time-dependent and often dynamic. It is necessary to apply signal processing techniques (e.g. Discrete Fourier Transform) to preprocess data in IoT scenarios. Compatibility of uncertainty detection software with typical IoT architectures is also important. The introduction of the so-called Agent-Based Framework (ABF) is proposed in the EMPIR Met4FoF project [15]. "Agents" are software modules encapsulating data processing steps that provide flexible on-demand data analysis and can run at various locations in the sensor network. An agent can receive data from a sensor, and pass it to an interpolation agent, which then provides it to a Fourier transform agent. Each agent provides proper uncertainty handling, which enables very flexible data analysis workflows for sensor network metrology. Fig. 7 shows the structure of a multi-agent system in which each agent module contains the necessary information about the sensor, calibration data, specific ways to calculate the measured value and associated uncertainty at any given time, and properties for evaluating the measurement results. This calculation may include more complex methods such as filtering or deconvolution [16].

The data from the sensor network, which is represented by a set of "sensor agents", is transferred to the "Data Analysis Agent" through the interface of the "Communication and Control Agent". "The Data Analysis Agent" applies the methods of processing mentioned above and classifies or recognizes images based on the aggregated data. The "Decision Agent" automatically generates and displays a report on the results and quality of measurements based on the analysis data. The described structure is flexible, which allows reconfiguring the network topology during its operation. This corresponds to the basic concept of metrological support for Industry 4.0.

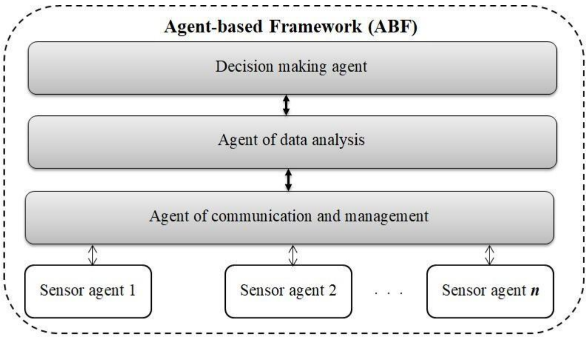


Fig. 7. The Structure of Agent-based Framework for evaluation of measurement results in IoT sensor networks

4.6. Application of Digital Calibration Certificates in Industry 4.0 and IoT

The implementation of Digital Calibration Certificates (DCC) in modern industry and IoT is a perspective solution. Calibration certificates are important metrological documents. DCC applications should include electronic storage, authenticated, encrypted and signed transmission, and consistent interpretation of calibration results. At the same time, the DCC format must be internationally recognized, machine-readable and interpretable.

The SI unit-based data model (D-SI) described above and the machine-readable XML data exchange format are recommended for representing the measured values. This model has been developed as part of the European research project SmartCom 17IND02 [17, 18]. DCC provides unique and global identification and storage of the properties of the calibration object and verifies metrological traceability.

The general structure of the DCC consists of four parts:

1. Administrative data (mandatory) – for clear identification of the calibration laboratory, calibration object, calibration customer, etc.;
2. Measurement results (mandatory) – contains digital measurement data in SI units in a strictly defined format, as well as text blocks with explanations;
3. Comments (optional) – contains specific information about the measurement process, which serves to further explain the measurement results;
4. Document (optional) – may contain the full calibration results in a format that is easy to read (pdf file).

XML is provided as a data format with corresponding schema files.

For cryptographic data protection, electronic signatures, electronic seals, and electronic time stamps must be applied to ensure the integrity and authenticity of the DCC, subject to legally approved procedures. The process of transforming analogue to digital calibration certificates is complex and multifaceted. Special attention has been given to machine reading and machine interpretation in the development of the above XML-based data exchange model. [19, 20]. 5. Conclusions

Metrological support for sensor networks in the IoT combines several aspects of metrology, signal processing, semantics, and web technologies. They need to be considered in the processing and metrological evaluation of sensor networks. However, a clear metrological framework for sensor networks has not yet been established. Current metrology guidelines focus on individual measurement devices and quantities. This is also true for the organization of metrology institutes and calibration laboratories. It is important to emphasize that elements of metrological support such as dynamic calibration of digital sensors, low-cost calibration of MEMS sensors, digital representation of metrological metadata, uncertainty assessment and propagation, and semantic modelling of sensor network information are highly developed. Further research is needed to integrate these aspects into a coherent IoT framework. It is essential to develop a systematic metrological approach for the overall assessment of sensor networks.

Addressing metrology-related challenges is critical to ensuring accurate, reliable, and trustworthy measurement data, even as the IoT offers numerous opportunities for innovation and efficiency across industries. Collaboration between industry stakeholders, standardization bodies and academia is essential to address these challenges and improve metrology in IoT applications.

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7. Mutual claims of authors

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References

[1] B. Jeckelmann, R. Edelmaier *Metrological Infrastructure.* Berlin, Boston: De Gruyter Oldenbourg; 2023. doi:10.1515/9783110715835

[2] E. Balestrieri, L. De Vito, F. Lamonaca, F. Picariello, S. Rapuano, I. Tudosa, Research challenges in Measurement for Internet of Things systems, Acta IMEKO vol. 7, no 4, 2018, pp. 82-94. doi: 10.21014/acta_imeko.v7i4.675

[3] Sascha Eichstädt, Anupam P. Vedurmudi, Maximilian Gruber, Daniel Hutzschenreuter, Fundamental aspects in sensor network metrology, Acta IMEKO, vol. 12, no 1, 2023. doi:10.21014/ACTAIMEKO.V12I1.1417

[4] S. Hackel, F. Hartig, J. Hornig, and T. Wiedenh, The digital calibration certificate, PTB – Mitteilungen Forschen und Prufen, vol. 127, no. 4, 2017, pp. 75–81. doi:10.7795/ 310.20170403

[5] T. Mustapää, J. Autiosalo, P. Nikander, J. E. Siegel and R. Viitala, Digital Metrology for the Internet of Things, *Conference: 2020 Global Internet of Things Summit (GIoTS),* Dublin, Ireland, pp. 1-6, 2020, doi:10.1109/ GIOTS49054.2020.9119603.

[6] J. M. Barcelo-Ordinas, M. Doudou, J. Garcia-Vidal, and N. Badache, Self-calibration methods for uncontrolled environments in sensor networks: A reference survey, Ad Hoc Networks, vol. 88, pp. 142–159, 2019. doi:10.1016/j.adhoc. 2019.01.008.

[7] T. Schneider, N. Helwig, A. Schütze, Industrial condition monitoring with smart sensors using automated feature extraction and selection, Measurement Science and Techno- logy, vol. 29, no 9, 2018. doi: 10.1088/1361-6501/aad1d4

[8] Met4FoF – metrology for Factory of the Future – Tutorial on the one-touch calibration of MEMS temperature sensors, 2021. [Online]. Available: https://www.ptb.de/empir2018/ met4fof/home/

[9] B. Seeger, T. Bruns, Primary calibration of mechanical sensors with digital output for dynamic applications, Acta IMEKO, vol. 10, no 3, 2021, pp. 177-184. doi:10.21014/acta_imeko.v10i3.1075

[10] D. Hutzschenreuter et al., SmartCom Digital System of Units (DSI) Guide for the use of the metadata format used in metrology for the easy-to-use, safe, harmonised and unambiguous digital transfer of metrological data – Second Edition, 2020. doi: 10.5281/zenodo.3816686

[11] S. Eichstädt, M. Gruber, A. P. Vedurmudi, B. Seeger, T. Bruns, G. Kok, Toward smart traceability for digital sensors and the industrial Internet of Things, Sensors, vol. 21, no. 6, 2021. doi: 10.3390/s21062019

[12] Why OPC UA is so important, Indusoft Digital Manu- facturing, 2022. [Online]. Available: https://indusoft.com.ua/ blog/2022/05/18/chomu-opc-ua-takij-vazhlivij/

[13] J. Wright Siunitx – A comprehensive (SI) units package, Version v2.7s, [Online]. Available: http://mirrors.ctan.org/ macros/latex/contrib/siunitx/siunit

[14] IEC TS 62720:2017. Identification of units of measurements for computer-based processing, 2017.

[15] S. Eichstädt, C. Elster, I. M. Smith, T. J. Esward, Evaluation of dynamic measurement uncertainty – an open-source software package to bridge theory and practice, Journal of Sensors and Sensor Systems vol. 6, 2017, pp. 97-105. doi: 10.5194/jsss-6-97-2017

[16] O. Vasilevskyi. Conception of metrological assurance in Industry 4.0, Information technologies and computer enginery, vol. 48, no. 2, 2020. P. 37-44. doi: 10.31649/1999-9941-2020-48-2-37-44

[17] Communication and validation of smart data in IoT- networks, Publishable Summary for 17IND02 SmartCom, 2021. [Online]. Available: https://www.ptb.de/empir2018/ smartcom/project

[18] Hutzschenreuter, D., Härtig, F., Wiedenhöfer, T., Hackel, S. G., Scheibner, A., Smith, I., Brown, C., & Wiebke Heeren, SmartCom Digital-SI (D-SI) XML exchange format for metrological data version 1.3.1 (1.3.1), Zenodo, 2020. doi:10.5281/zenodo.3826517

[19] S. Hackel, F. Härtig, T. Schrader, A. Scheibner, J. Loewe, L. Doering, B. Gloger, J. Jagieniak, D. Hutzschenreuter, and G. Söylev-Öktem. The fundamental architecture of the DCC. Measurement: Sensors, 18:100354, 2021. doi:10.1016/ j.measen.2021.100354.

[20] J. Nummiluikki, S. Saxholm, A Kärkkäinen, S. Koskinen. Digital Calibration Certificate in an Industrial Application, Acta IMEKO, vol. 12, no. 1 (2023). doi: 10.21014/actaimeko, v.12i1.1402.