Metrology for next generation “Phygital Sensors”

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Abstract:

Commonly speaking a ‘sensor’ is a device that produces an output signal quantitatively related to a certain physical phenomenon; if the output signal is provided in a digital form, it is referred in terms of ‘digital sensor’. As is known, these devices are produced in the order of million/week and are widely used for the management of “smart systems” now commonplace in everyday life, such as automotive, domotics, smart-industry, cooperative robotics (“cobots”), robotic assisted surgery, as well as for advanced monitoring of infrastructures and ecosystems; moreover, digital sensors are the foundation of the “digital twins” technology development, and support the actualization of the “Digital Earth” purposes. However, in many cases, since these sensors manage interaction processes with humans (e.g., driver assistant control, physiological data, remote surgery, environmental hazard…), their technological performance must be actually recognized as safe and trustworthy. Recently, both manufacturers and end users have begun to question the actual reliability of sensors used in particularly complex applications, and see value in traceable chain to calibration and accreditation national laboratories. Indeed, the methods applied for metrological calibration of measuring instruments, against primary or secondary standards, can allow to accurately quantify the performance of these sensors, with respect to traceable physical quantities, providing certified statements of the effective ‘sensitivity’ (and related uncertainties), as the ratio between the digital output (reaction) and the physical input (stimulus). In that meaning, once calibrated, a digital sensor can be properly considered as a physical-digital sensor, i.e. a device, interfacing the physical world, sensitive to a specific variation of a known physical quantity, and able to convert it into a digital signal output (with known accuracy, precision and reliability), readable for an observer, exploitable by interconnected instruments, and for actuators control. Currently, although no pertinent Standards are yet available for the calibration of ‘physical-digital sensors’, some National Metrology Institutes are putting into practice appropriate calibration procedures and methods to fill this important lack, as described in this paper.

Keywords

- “Phygital sensors”,
- calibration,
- metrological characterization,
- sensitivity,
- statistical approaches

Introduction

A common agreed metrological framework, allowing to provide quantitative technical features of physical-digital sensors (or "phygital sensor"), is still unavailable. At present days, technical performance, mechanical characteristics, responsiveness and peculiar properties are uniquely provided by manufacturers without traceable methods, without information on data quality, in terms of accuracy and precision, and without referenced statements of the adopted procedures and methods of calibration (or adjustment). As a consequence, by referring to the terminology defined in VIM [1], the current metrological attributes of measuring instruments, such as traceability, precision, resolution, accuracy and reliability of data, cannot be provided for digital sensors, thus often end-users implement custom calibration techniques (or more properly, custom adjustments), or they rely on datasheets provided by the manufacturers. Although the sensitivity (or the scale factor) is adjusted during the production process, in many applications there are several legal or insurance reasons for which it is preferable to use sensors calibrated in accredited and certified laboratories, according to the ISO 17025 standard [2].

Recently, some applicative protocols were published, e.g., IEEE Standard 2700-2017 [3], providing a common framework for sensors performance specification terminology, units, conditions, and limits. Indeed, the large deployment of sensors in engineering applications needs to be underpinned by new metrological approaches [4] –[6] allowing to support trustworthy and safe operation, linked to traceability chains, to guarantee higher quality management requirements. However, the IEEE 2700-2017 standard does not provide methods and technical procedures for evaluating the performance of physical-digital sensors, effectively delegating these activities to "good practice".

The relevance of these emerging needs in the field of metrology, has recently oriented the strategy plan of BIPM [7], in order to "identify and deliver the highest impact opportunities to support National Metrology Institutes (NMIs) priorities in, for example, the areas of "big data" and digital transformation", with the aim to provide suitable calibration procedures for these systems, against national primary standards, and to provide the traceability chain to the national laboratories and to the manufacturers, at present not yet available. As an example, by referring mechanical applications, within the Strategy 2021 to 2031 of the Consultative Committee for Acoustics, Ultrasound, and Vibration at BIPM [8], the vision is strongly oriented to the issue of digitalization and to the traceability of sensors with digital interfaces. Indeed, the metrology applied to digital sensors is particularly stimulated from both industrial needs and sensors manufacturers, and several NMIs worldwide are planning their activities along these perspectives, with the aim to link the digital sensors performance to the traceability chain, within the metrological hierarchy, based on recognized calibration procedures, ensuring comparability and reproducibility, from primary standard to end-users, as schematically represented in Fig. 1.

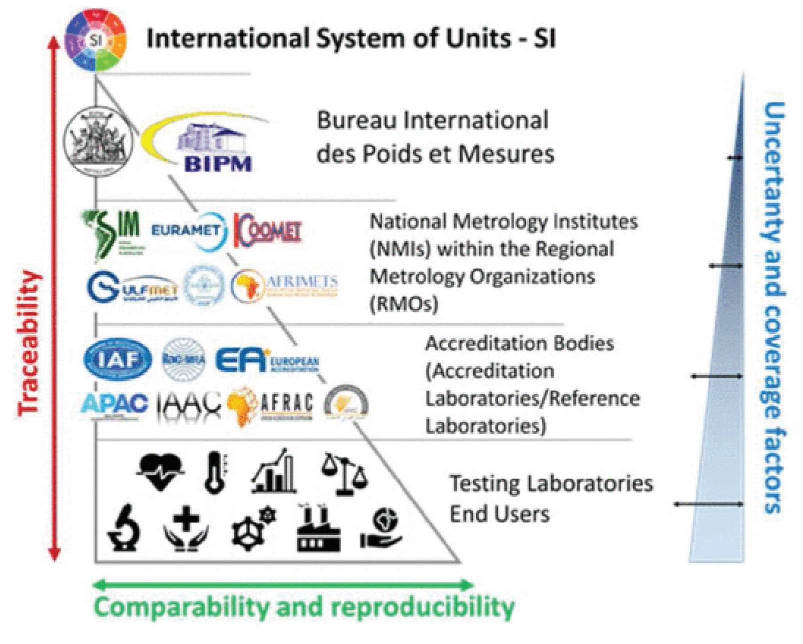

Fig. 1.
The metrological traceability chain and the propagation of SI.

The Actualization of a "Phygital Sensor"

In many everyday life applications (sometimes very sensitive ones), the increasingly widespread use of digital sensors, whose functioning and responsiveness are based on physical stimuli, needs recognized requirements of confidence, safety and reliability, in order to support services, monitoring, control, systems management…, with due accuracy and trustworthiness. Metrological approaches allow to meet these requirements, providing quantitative information on the sensors' performance and data quality. In that meaning, a 'digital sensor' can be considered as 'phygital', since its digital output is actually representative (and consistent) with the physical phenomenon which has induced it. In Fig. 2 a basic conceptualization of the functionality of a phygital sensor, with respect to a metrological approach, is schematically depicted.

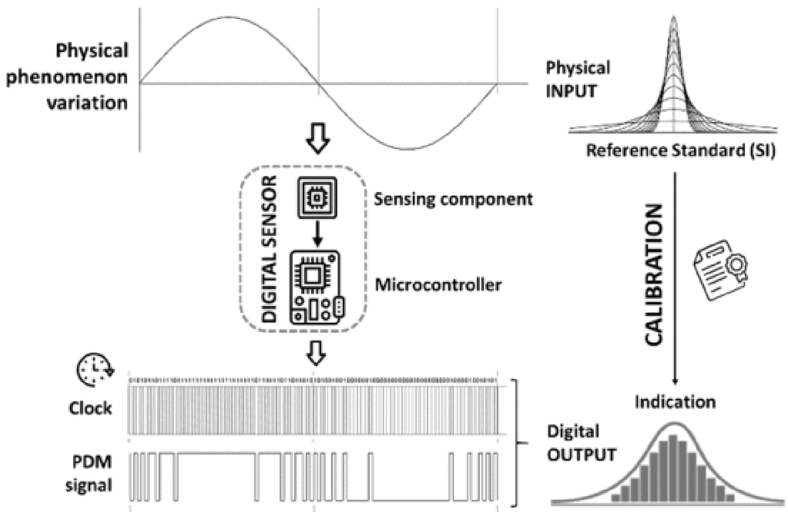

Fig. 2.
The functioning of a 'phygital sensor': the digital output is provided by the sensor, once subjected to a certain variation of a physical phenomenon, and the related metrological conceptualization.

As depicted in Fig. 2, a variation occurring in a certain physical phenomenon (the physical input), induces a proportional variation in the sensing component within the sensor; the sensing component transduces this variation as an electrical signal, that is quantized and digitized by an A/D converter, and is provided as a *bitstream* (the digital output), according to adopted form of modulation (e.g., a PDM signal). A calibration method allows to quantify (with a defined reliability) the relation between the reference standard physical input, and the related digital output indication, with information on precision (i.e., the width of data provided distribution), and accuracy (i.e., the closeness with the standard reference), as schematically shown in Fig.3.

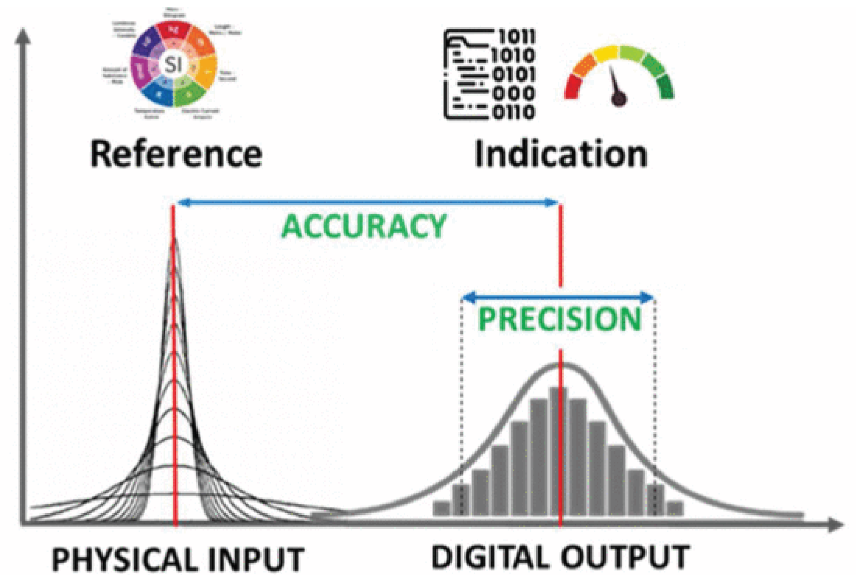

Fig. 3.
The fundamental metrological attributes, quantified from a calibration procedure, actualizing a 'phygital sensor'.

More properly, a metrological calibration allows to define the quantitative ratio between the value of the indication (within its uncertainties) provided by the sensor under calibration, and the value of the reference (within its uncertainties). This ratio is the sensor's metrological 'sensitivity', or better the 'digitized sensitivity', since the ratio is carried out between and a discretized function [9] and a continuous one (physical variation). The 'digitized sensitivity', as a calibration result, is not in conflict with the 'scale factor' provided by manufacturers, but it is a further quality attribute, which allows to support the trustworthiness of provided data, with reference to a well-defined traceable physical quantity, relying on the International System of Units (SI) of the Metro Convention.

Once a suitable calibration procedure is identified, in order to provide the metrological 'sensitivity' of a digital sensor, with well-defined and detailed uncertainty budget, it is expected that that sensor, once applied in operating conditions, is therefore able of providing quantitative and reliable indications of the physical phenomenon detected, in the form of digital output, with appropriate information on accuracy and precision. Nevertheless, since "these technologies have different mounting requirements, use different testing and calibration protocols, and use digital interfaces for data and communications" [8], the current standard requirements for the calibration cannot be always applied, thus tailored procedures, different analyses and methods need to be undertaken, in order to identify and quantify the actual sensitivity of digital sensors. As a further step, in order to validate the suitability of the calibration procedure, it is then necessary to verify its reproducibility, by establishing inter-laboratory comparisons, to trace back, along the traceability chain, the compatibility of indications provided in form of digital output. Moreover, since these sensors are produced in order of millions/week, it is impossible to individually calibrate each single sensor; therefore, it is necessary to identify a compatible similarity, or conformance, among all items based on statistical sampling methods to be applied for large-scale calibration, with the aim, "to reduce manufacturing costs while delivering statistically acceptable levels of performance and reliability" [8].

Therefore, the actualization of a 'phygital sensor' must be underpinned by a hierarchy of traditionally recognized metrological procedures, that meet at least the following basic requirements:

- Definition, realization and application of suitable (and agreed) calibration procedures, which guarantees traceability along the metrological chain, from SI to end users;
- Identification of the uncertainty contributions, which supply accuracy and precision to data provided, sensor resolution, and coverages factors compliant with operative conditions;
- Determination of comparability and reproducibility, supporting the trustworthiness in actual applications, and the compatibility of data provided;
- Providing evidence of self-similarity (or conformity assessment) among nominally identical sensors, and related confidence levels, by establishing suitable statistical approach for metrological attributes within quality management of products and processes.

The Metrological Approach

In the following, as a case study, a full metrological approach has been applied to a mechanical sensor with digital output (DUT), to provide the actual sensitivity (and related metrological attributes), toward the actualization of a true 'phygital sensor', at INRIM. At present day, on the basis of a literature survey, only four National Metrology Institutes (NMIs) worldwide, are involved to develop calibration methods for vibration of mechanical sensors with digital output, in static and dynamic conditions, namely at NIST (USA) [10] , NMIJ (Japan) [15–17], PTB (Germany) [18–21], and at INRIM (Italy) [22] –[25].

The DUT is a commercially available inertial module (iNEMO), namely a system-in-package featuring a high-performance 3-axis digital accelerometer, low power consuming (LSM6DSR) designed, realized, and produced by STmicrolectronics [26].

Calibration

A traditional calibration procedure (performed according pertinent Standards), allows to determine the metrological sensitivity of measuring instruments, providing the traceability to SI. Suitable calibration procedures can be tailored to provide accurate and reliable technical performance of a digital sensor, against a reference physical standard. Recently at INRIM a setup for calibration of digital accelerometer sensors in dynamic conditions (in the frequency domain) was developed. The calibration method is adapted to be compliant with ISO 16031-

11 [27]. In Fig. 4 the system is schematically depicted; the detailed description is in [23], [24].

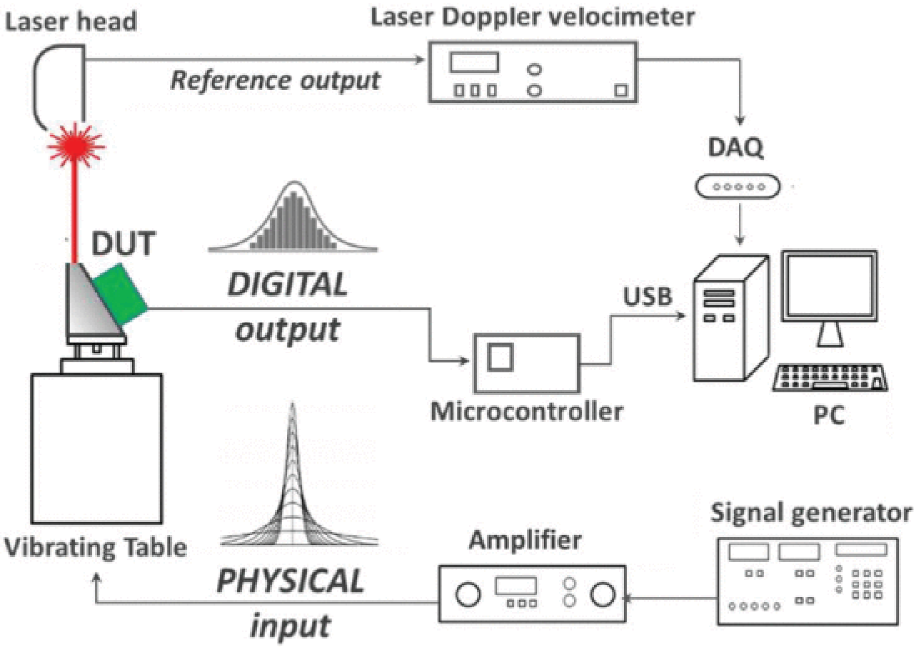

Fig. 4.
The set-up for mechanical-dynamical calibration of digital sensors (in frequency domain), developed at INRIM.

As shown in Fig. 4, the DUT is fixed on an inclined plane (itself screwed on a vibrating table). As a physical input, single frequency mechanical oscillations, with known amplitude in vertical direction (parallel to *g*), are provided. Actual frequency and amplitude of mechanical oscillations (the reference output) are measured by means of a LDV, employed as primary standard. The occurring vertical oscillation is decomposed in 3 components along the inclined plane, in order to simultaneously acquire the digital output of the 3 sensitive axes of the DUT, and the related crosstalk effects. The sensitivity, as calibration results, is provided as the ratio between the values of the corresponding *bitstream* (converted into a decimal number, D) and the unit of the reference physical quantity (acceleration, in $m \cdot s^{-2}$), i.e., $D/m \cdot s^{-2}$.

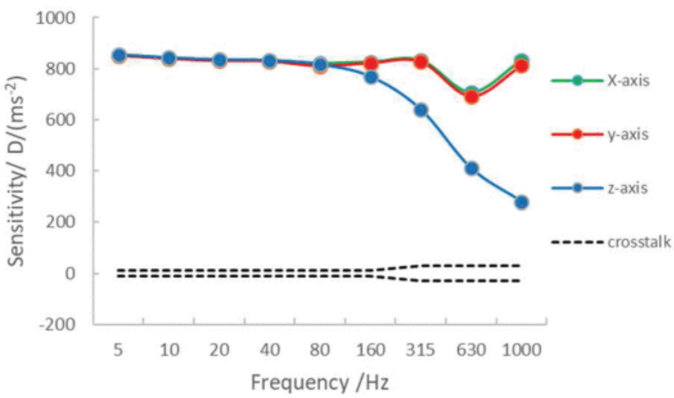

Fig. 5.
The calibration result: the sensitivity values of the 3 axes (and the interval including the cross-sensitivities), as a function of frequency.

Uncertainties contributions

Each single bullet, in the graph of Fig. 5, represent a specific value of sensitivity, as a function of frequency, as a result of calibration against the primary standard. E.g., at 10 Hz, the sensitivity of *x*-axis results 843D/m·s^{-2}. Nevertheless, this value is affected by several uncertainties, that should be accurately identified. The uncertainties depend on the calibration system, on the reference physical input, and on intrinsic features of the DUT, such as possible misalignment of the internal sensitive axes, and sampling rate synchronization. In Fig. 6 the quantities contributing to the uncertainty budget, are depicted.

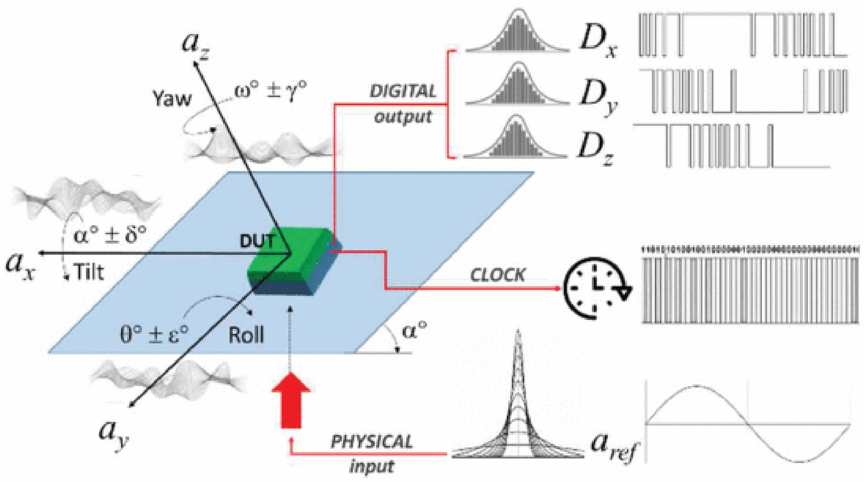

Fig. 6.
Schematic representation of uncertainty affecting the calibration.

Namely, the uncertainty contributions are mainly due to the intrinsic systematic effects of the calibration setup, such as the reference acceleration a_{ref} (the physical input), the pitch, roll, and yaw angles, and by systematic effect occurring along the 3 acceleration components (a_x, a_y, a_z), and the phases differences along the 3 axes, a detailed description is in [24], [25]. Moreover, the digital output could be affected by improper synchronization, which depends on the variability of sampling rate process [18], [28], and by undetermined internal misalignments [10], [14], [29]. Once all variables are identified, and the related uncertainties are quantified, by applying the general rule of random propagation errors, according to GUM [30], the associated uncertainties are attributed to all sensitivity values [23], reported in Fig 5. By way of example, the sensitivity of *x*-axis at 10 Hz is expressed as 843±16D/m·s^{-2}, i.e., with a precision of 2%. In the following graph of Fig 7, the actual precision of the sensitivity value (represented by the Gaussian function), and the associated uncertainty, are represented.

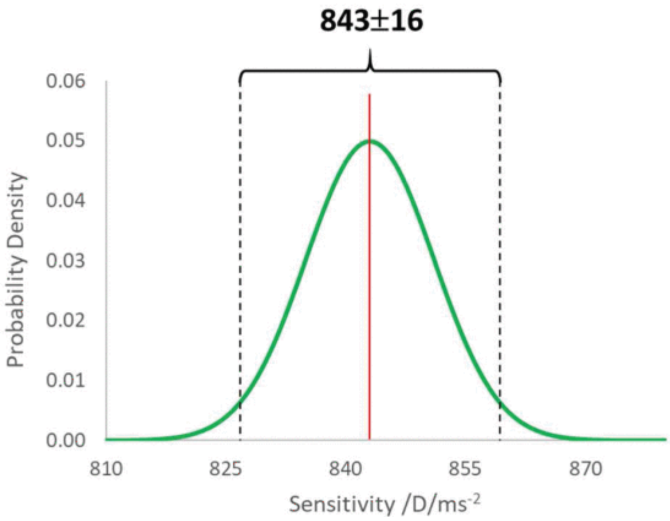

Fig. 7.
The actual precision of the sensitivity value, and its uncertainty.

On the basis of calibration, it is possible to identify the actual resolution of the sensor as well. Indeed, by considering that, at 10 Hz the sensor provides 843D/m·s^{-2}, it is expected a nominal resolution of 1D=0.0012m·s^{-2}. Nevertheless, by taking into account the observed precision (i.e., ±16D/m·s^{-2}), the effective resolution is 0.042m·s^{-2}.

Although calibrations are conventionally performed in compliance with constant climatic requirements, harsh or critical environmental conditions, such as large temperature variation, humidity, magnetic fields, mechanical stress… are further contributes of uncertainty, affecting the sensor performance in operative conditions. Then, it could be useful also to verify the stability (or the dependency) of sensor indications with respect to known physical occurrences [31].

Comparability and reproducibility

On the basis of a double-blind “multi-bilateral” comparison [32], carried out between two laboratories, 25 nominally identical DUTs are investigated, in order to assess the conformity, form reproducibility of data provided by two different calibration methods [33], [34]. In Fig. 8, by way of example, the sensitivity values distributions, measured at 10 Hz (for the sensitivity x−axis), determined in the two labs, are shown.

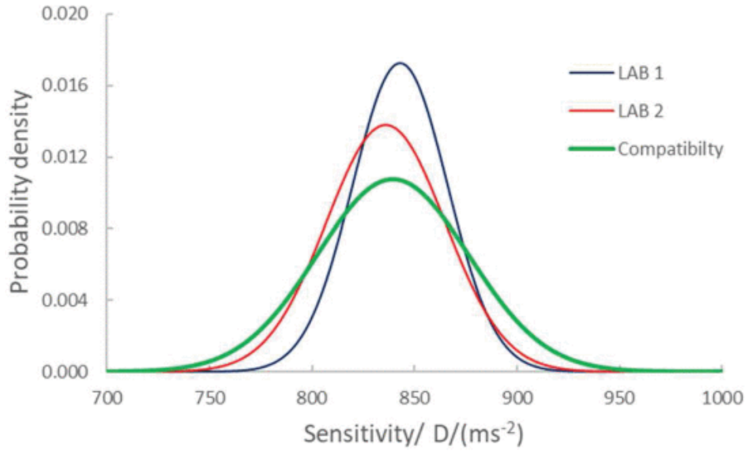

Fig. 8.
Average sensitivity distributions at 10 Hz, for *x*-axis, measured in the two laboratory, with independent calibration methods. Dotted line is the resulting sensitivity according to the reproducibility.

The sensitivity distributions are the average values among 25 DUTs. In Lab 1, the sensitivity results 843±23D/m·s^{-2}, in Lab 2 it is found 836±29D/m·s^{-2}. The compatibility of comparison is evaluated by calculating the normalized error E_n [35]: if E_n<1, distributions are compatible, and can be merged. As expected, the reproducibility "enlarges" the uncertainty of the calibration results, and the resulting sensitivity at 10 Hz for x−axis is then 840±37D/m·s^{-2}, then with a precision of 5%.

A conformity assessment of large-scale 'calibration'

As a last step, calibration is performed on 100 DUTs (nominally identical, from a same batch) [36]. This investigation allows to evaluate the actual self-similarity among measured sensitivity (such as a conformity among DUTs), by using a single calibration method. In Fig. 9, the results of calibration, performed in the frequency range between 5 Hz and 1 kHz, are shown.

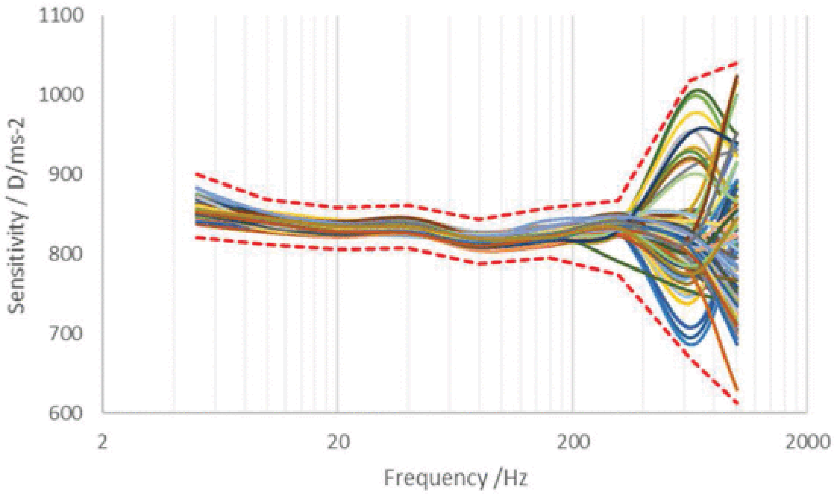

Fig. 9.
The comparison among 100 DUTS sensitivities (as a function of frequency, from 5 Hz up to 1 kHz) on *x*-axis. Dotted red lines represent the absolute MIN and absolute MAX values (precautionary, ±16D/m·s^{-2}).

At a first glance, it is possible to observe a quite defined self-similarity from 5 Hz up to 200 Hz, and large dispersions up to 1 kHz. In order to quantify the similarity among results, the conformity of sensitivity is determined by applying methods largely used in quality control management. By only considering the sensitivity values at 10 Hz on *x*-axis, the corresponding distribution is calculated. As an example, in Fig. 10, the observed distribution of sensitivity (on the x−axis, at 10 Hz), among 100 DUTs is shown. This calculation is then recursively applied for each sensitivity axis, and each frequency investigated in calibration, between 5 Hz and 1 kHz.

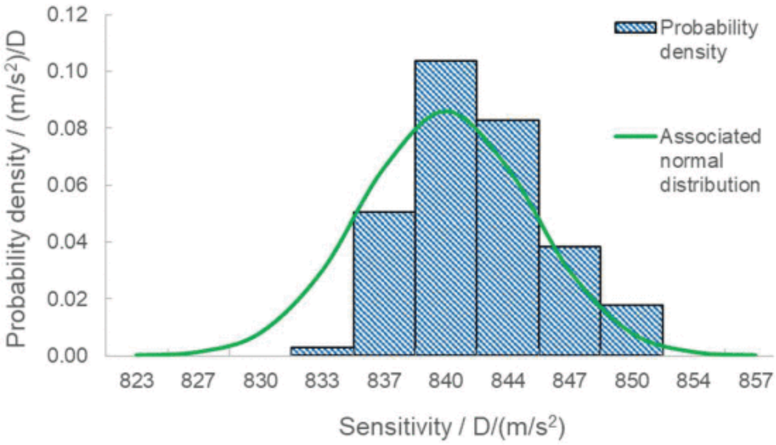

Fig. 10.
Actual distribution of sensitivities (on *x*-axis, at 10 Hz) from the individual calibration of the 100 DUTS, and the associated Gaussian distribution.

The graph of Fig. 10 shows the actual distribution of sensitivity values (without considering the related associated uncertainties). This analysis allows to quantify the similarity (or qualitative conformity) among DTUs indications. In particular, the average sensitivity (among 100 values) is 840±9D/m·s^{-2}, within a minimum of 828D/m·s^{-2} and a maximum of 853D/m·s^{-2}. Actually, by taking into account also the related associated uncertainties (as discussed above), a comprehensive distribution should be built by merging the values of sensitivity, within proper precision, as shown in the graph of Fig. 11.

In the graph, red normal distributions are related to the minimum and maximum sensitivity values, black normal distributions are 100 DUTs sensitivities, and dotted green normal distribution represents the actual range of sensitivity at 10 Hz. This range of sensitivity allows to provide a suitable coverage factor for the experimental results, with a confidence level of 95%.

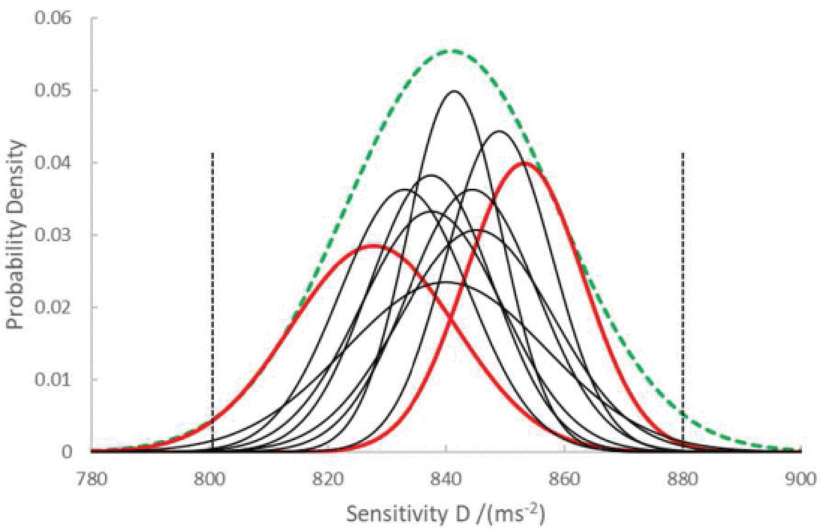

Fig. 11.
Example of sensitivities collection (at 10 Hz on *x*-axis), with distributions uncertainty-dependent. Max and Min values (red), cumulated distribution (dotted green), within the coverage factor limits (dotted black).

Conclusions

Unlike traditional measuring instruments and devices, digital sensors (at present day) are not conceived and designed to provide accurate, precise and traceable measurements of physical phenomena, but only to manage the functionality of "smart systems", by activating actuators, by providing alert, by checking out-of-threshold signals, and so on. In these applications, the technical performance of digital sensors can be considered satisfactory and (within certain conditions) safe. On the other hand, even today, many monitoring and survey systems and networks (used in the most varied applications) are supported by traditional measurement tools, with high management costs and energy consuming, intrinsic fragility, and invasiveness (in terms of mass or volume).

In these applications, as well as in "smart systems", digital sensors (once calibrated) can be advantageously used, either in place of or alongside traditional instrumentation. In this way it is possible to greatly improve the potential of the monitoring systems, increasing the number of sensors to support the survey, at limited cost and saving energy, by maintaining the high reliability of data provided. Furthermore, the use of calibrated digital sensors in existing or under development functional "smart systems" (such as autonomous driving, traffic flow management, intelligent transport systems, robotic assisted surgery, remote diagnosis, smart grids, smart manufacturing, "cobotics", …) would bring further advantages, as the safety and reliability of data management would be greatly improved.

A metrological approach, allowing to actualize an accurate, precise and trustworthy 'phygital sensor', can support an actual digital transformation of the traditional monitoring and survey methods, by guaranteeing safe and reliable data, traceability of information, and by ensuring a proper and suitable quantification of the occurring physical phenomena. Besides, "smart systems" with integrated 'phygital sensors' will be certainly more trustworthy (and much more competitive) than "smart systems" with not calibrated sensors, since data supplied can be considered effectively representative of measured phenomena, beyond to be compatible and reproducible (and traceable).

However, at present, there are neither available standard procedures nor fully agreed protocols to provide a detailed and comprehensive metrological characterization of digital-physical sensors, and technical performance are supplied by manufacturers without traceable methods and reference standards. This lack prevents a safe and trustworthy

development of expected digitalization, in particular in applications in which direct or indirect interactions with humans, and human activities, need to be managed.
In this paper are briefly summarized the most recent activities, developed in the field of applied metrology (in National Metrological Institutes and advanced academic laboratories), toward a dedicated metrology to supply suitable calibration methods for digital sensors. Moreover, a statistical procedure for a ‘conformity assessment’ of large-scale calibration is also proposed, since “the industry has moved from testing and calibrating every device towards statistical sampling to reduce manufacturing costs while delivering statistically acceptable levels of performance and reliability” [8].
These activities are specifically indicated in the strategic plan of BIPM, and of several Consultative Committees within it, to support the quality and reliability of digital transformation processes, and the actualization of a safe and trustworthy digitalization.

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