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Metrological Assurance and Standardization of Advanced Tools and Technologies for nondestructive Testing and Condition Monitoring (NDT4.0)

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ABSTRACT

In the article urgent tasks of the development of NDT and CM metrological assurance, as well as problems of standardization of general principles and specific technical solutions in the context of the fourth industrial revolution main trends are discussed. The following questions are considered: Development of the NDT metrological assurance based on the concept of multi-parameter measurements, development of standards for remote adjustment and calibration of intelligent sensors in distributed measuring networks. Attestation and verification issues (metrological assurance) of digital models (twins) for inspected objects and measuring and testing devices – Methodological principles for constructing self-monitoring and self-calibrating intelligent measuring transducers (sensors) for cyber-physical systems of smart manufacturing and distributed condition monitoring systems (quality infrastructure). - Development of standards for various components of distributed CM systems (smart sensors interfaces and protocols for transmitting information, software, and hardware platforms for collecting and processing information, digital twins of tools and control objects) embedded in the overall standardization system for smart industries, which realized key principles of Industry 4.0 in terms of compatibility, transparency, technical support, and decentralization of management decisions based on intelligence machine algorithms.

KEYWORDS

Intelligent sensors; self-calibration; multi-parameter measurements; cyber-physical systems; digital twins

Introduction

The article's purpose is to analyze technological and regulatory trends in the metrological support and standardization of NDT in the conditions of the 4th Industrial revolution and to formulate the tasks facing the world community of NDT specialists in these areas. **The introduction** examines the general directions of modern development of measurement and control and their integration into the Industry 4.0 system. The **first chapter** analyzes the problems of metrological support of NDT tools and methods in the context of solving the problem of modern NDT procedures certification. The concept

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of NDT as multiparameter measurements is considered, an example of this concept application for electromagnetic thickness measurement of coatings is given. The **second chapter** presents the authors approach to the problem digital models certification of controlled objects (digital twins) and control devices (virtual devices). The **third chapter** is devoted to the issues of ensuring the measurement and testing information reliability through the introduction of intelligent sensors with self-monitoring and self-calibration functions. **Chapter 4** attempts to set standardization objectives to implement the solutions discussed in the previous chapters.

Technical and technological trends of the fourth industrial revolution are directly related to the development of measurement technics and metrology [1,2], which include nondestructive testing (NDT), condition monitoring (CM) and technical diagnostics.

The main directions of this development are:

(1) The development of "smart" instruments for measurement and control, as well as off-line "smart sensors" with self-monitoring and self-calibration functions [3,4], capable of connecting to information networks for the exchange of information using modern digital interfaces, including wireless ones.
(2) Creation of hardware and digital platforms for distributed systems of condition control and monitoring using modern information technologies, including cloud ones [5].
(3) Development of digital models of controlled objects for carrying out their technical diagnostics, and digital models of measuring and control instruments for controlled parameters evaluation [6]. One of the key conditions in creating such digital models is the use of artificial intelligence technologies based on neural networks using Big Data [7].

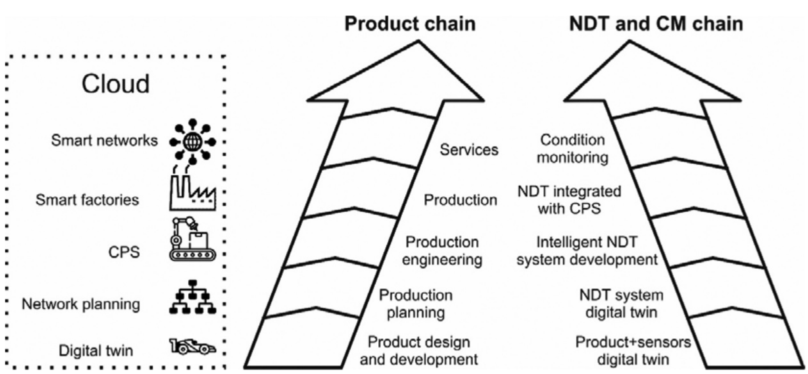

Figure 1. End-to-end system engineering across the entire value chain [13] with integrated NDT and CM.

The result of the development of these directions are the following possibilities:

(1) Creation of distributed automated control systems and monitoring of complex technical objects [8], including Structural health monitoring [9].
(2) Creation of environmental monitoring systems [10].
(3) The development of cyber-physical systems (CPS), including automated “smart” production [11].
(4) The introduction of “smart grids” in the energy sector, transport, urban environment, etc [12].

The listed intelligent systems during their creation will be naturally integrated into production chains based on the principles of Industry 4.0. One of these principles in accordance with [13] is digital end-to-end engineering across the entire value chain of both the product and the associated manufacturing system. In turn, the design of the NDT and CM systems themselves should be based on the same principles and integrated into the process of creating controlled objects. Figure 1 shows a diagram of the product creation chain [13], supplemented by a diagram of the process of developing NDT and CM system with its simultaneous integration into the production chain. In accordance with the proposed scheme, at the stage of product development, its physical digital model (twin) is developed and its controlled parameters are determined. Based on this model, the necessary testing methods and means are determined and a digital model of the control system itself is created, which takes into account the characteristics of the used measuring and testing tools (including intelligent measuring sensors). The embodiment of such a model should be an intelligent NDT system integrated directly into the production line (cyber-physical system). At the end of the product, creation chain should be a CM system based on sensors with the functions of self-monitoring and self-calibration.

1. Metrological Problems of NDT and CM

The listed tendencies and prospects are common to all means and methods of measurement and testing that implement the general principles of building modern smart industries and distributed systems. At the same time, the NDT industry has its own specific features considered in [14].

To create monitoring and automatic control systems using nondestructive testing tools, including cyber-physical systems and smart networks, it is necessary to obtain accurate, reliable, and confident information in the process of NDT and CM. At present, the problem limiting the development of NDT and CM in accordance with the requirements of Industry 4.0 is the significant

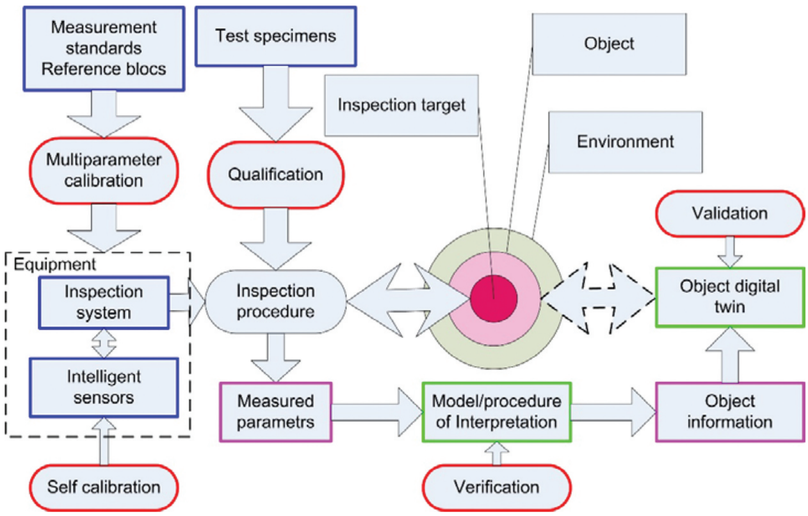

Figure 2. Block diagram of NDT system with elements of qualification of equipment, methods and digital models.

subjective role of a specific specialist in monitoring and analyzing the data obtained. As a result, a prerequisite for the certification of most NDT systems is the certification of personnel. One of the ways to reduce the influence of this factor is the introduction of an artificial intelligence system both in the software modules of NDT devices and in the development of digital twins of inspected objects [15]. The problem of shifts human factors from the inspector to the person implementing the AI or automation exists and actively studying [16]. At the same time, the automation of the nondestructive testing process will inevitably reduce the influence of random factors on its result. Also, to create a qualification system for NDT inspection systems that meets the requirements of Industry 4.0, it is necessary to solve the following tasks: metrological support of NDT devices; verification of digital models, which are an integral part of devices and systems used in processing of the received information; validation of digital twins of inspected objects. To solve the problem of assessing the reliability and confidence of NDT, it is proposed to apply the approaches and mathematical methods used by metrologists [17]. Ensuring the uniformity of measurements in this area is necessary to obtain reproducible and reliable results. The requirements for measuring equipment for Industry 4.0 imply the maximum automation of measurement processes and monitoring of measuring instruments metrological serviceability. To meet these requirements, it is necessary to unify the equipment and applied methods, as well as to overcome the influence of subjective factors (staff qualifications) on the result of NDT. This problem is solved by ensuring metrological traceability of the measurement results performed during the NDT to primary standards or reference methods. Some issues related to general points and differences in the certification of measurement tools and methods and NDT are considered in [18]. The NDT uses the term sizing in accordance with ISO/TS 18173, which refers directly to measurements. A number of nondestructive testing methods imply measurements, which is confirmed by relevant international standards directly related to the NDT field, like ISO 16809 and ISO 16831 for ultrasonic methods and equipment. Sections of standards related to metrological support of the considered methods and tasks included, for example, in ISO 2360, ISO 2178, ISO 21968 for electromagnetic coating thickness measurements methods.

A diagram describing the structure of the NDT system, including elements of calibration, verification, and validation, is presented in Figure 2. The following elements of NDT qualification system are proposed in this scheme:

- Ensuring the traceability of measurement information obtained during inspection procedures to the primary standards (calibration) to ensure the unity and reliability of the source data.
- Technical and methodological solutions that ensure self-monitoring and self-calibration of primary measuring transducers (intelligent sensors).
- Qualification of inspection procedure based on comprehensive tests on real objects or test specimens (reference blocks).
- Metrological support and verification of methods for interpreting received data, including sensor digital models.
- Metrological support and validation of computational models (digital twins) of inspected objects.

In addition, for distributed systems of NDT and CM, it is also necessary to provide the definition and standardization of the metrological characteristics of communication channels that affect the increase of uncertainty or loss of information during data transmission.

The most important step in the development of the NDT system metrological support, according to the authors, is a systems concept of NDT measurements as multi-parameter one, i.e., taking into account the simultaneous influence of a number of controlled object parameters on the measurement result.

The measurements of wall or coating thicknesses using ultrasonic, electromagnetic, or other methods of NDT can be an example of multi-parameter measurements. The specificity of such measurements is that for the corresponding primary measuring transducers it is impossible to unambiguously separate informative and interfering parameters. Particularly, eddy current thickness gauges implementing amplitude-, phase-, and frequency-sensitive eddy current methods of measurement based on an analysis of the magnetic field of eddy currents induced in the test object are widely used to measure the thickness of metal coatings.

The measurement results of these devices depend on several groups of parameters: electro-physical (specific conductivity of the coating materials σ_c and base σ_{base}, the complex relative magnetic permeability of the base material μ_{base}) and geometrical (coating thickness T_c, roughness, radius of surface curvature, etc.) [19]. To ensure the traceability of thickness measurements T_c by the described method, it is necessary to use reference measures assigned (certified) with over all specified parameters [20]. To solve this problem, the development of a distributed reference measurement standard is being currently completed at the Russian National Mendeleev Institute for Metrology (VNIIM). It provides measurements of following parameters of reference measures:

- geometric parameters;
- conductivity of the base σ_{base} by Van der Pauw method;
- conductivity σ_c of the coating material using a high-frequency eddy-current transducer with a wave excitation winding [21];
- complex relative magnetic permeability μ on ring samples using a permeameter with the possibility of transmitting the value of this parameter to the base of the measure (μ_{base}) [22].

The creation of such reference standard should dramatically increase the accuracy and reliability of the measurement results in this area.

2. Metrological Assurance of Digital Models (Twins) for Inspected Objects, and for Measuring and Testing Devices

When developing promising means for measuring and NDT, it must be kept in mind that software systems for creating digital models (DM) of devices and inspected objects, calculating controlled parameters and assessing the reliability of objects, and, as a result, DMs themselves, have a number of limitations, including the following factors:

- the adequacy and completeness of the physical models used;
- the applicability of the used mathematical methods;
- the accuracy of setting the parameters of the simulated objects and the boundary conditions for their application.

Incorrect use of physical models and mathematical methods for calculating the parameters of digital models, as well as errors or inaccuracy when setting physical parameters, can lead to erroneous results in predicting the properties and behavior of real objects.

When developing DM, scientists and developers around the world widely use a variety of modeling tools, most of which are closed-source software. Real

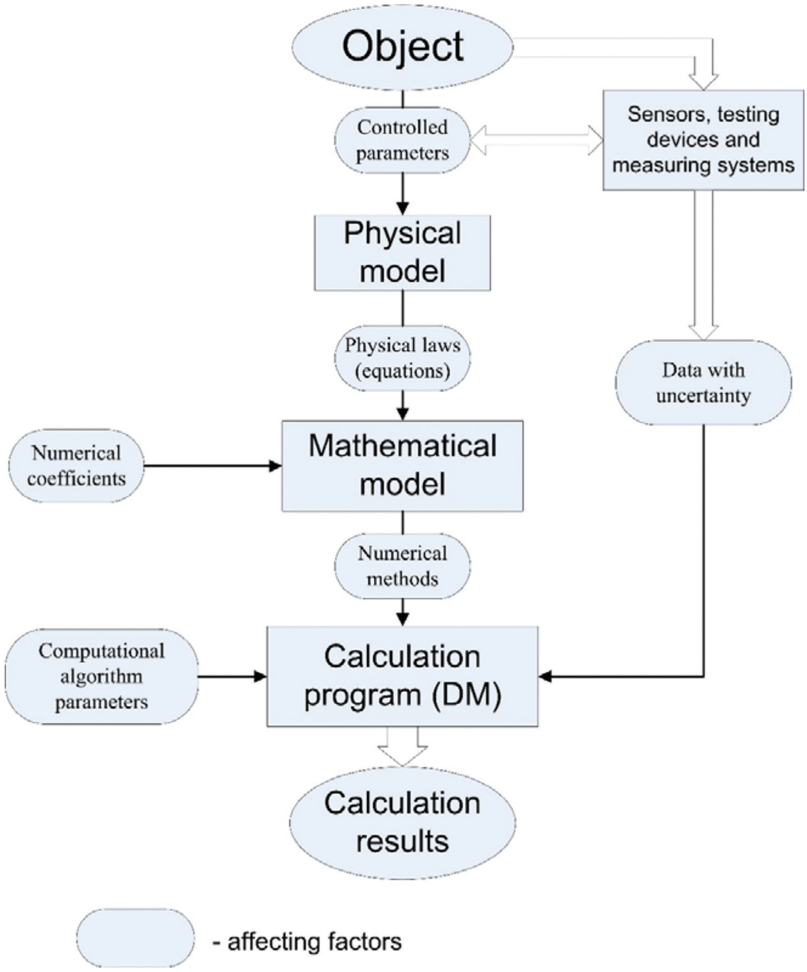

Figure 3. Factors affecting the development and operation of a digital model (twin).

products built on the basis of these models, one way or another, must pass full-scale tests. With the widespread adoption of digital models to predict behavior and make decisions regarding potentially dangerous objects, it is necessary to take action to prevent their uncontrolled and unskilled use. This will require the creation of an organizational and legal system and engineering infrastructure to establish the completeness and adequacy of digital models (verification), establish limitations on their applicability (validation), and monitor the correct use of digital models in real conditions. In particular, a digital model that is approved for use in critical or potentially hazardous areas will be required to undergo a full-scale test in one form or another. The use of such a model for creating and controlling a real object will have to be done by qualified (certified) specialists who are responsible for the correct application of the model and setting the parameters of the control object.

Currently, there are no approaches unified and well established for assessing the quality of DM "measuring instrument – object of control." For practical applications, a kind of "metrological support" of DM should be developed. Modern metrology considers two measurement methods: direct, in which the sought quantity value is obtained directly from the measuring instrument, and indirect, in which the sought quantity value is determined on the basis of the results of direct measurements of other quantities, functionally related with sought quantity. In the first case, the device is considered as a "black box" and its metrological characteristics are evaluated by direct calibration using a standard and the evaluation of influencing parameters. In the second case, the uncertainty of each of the measured quantities is estimated and their influence on the final result is calculated. The DM used to obtain measurement information can be considered as a measuring transducer and classical metrology methods can be applied to it.

In the case of the "black box" model, the value of input quantities and calculation results are compared. As reference values, the results of theoretical calculations should be taken in the presence of known mathematical dependencies or experimental data. This method allows model verification, but does not provide information about the cause of possible errors and optimization paths. In Figure 3 presented factors, affecting the parameters of a digital model during its development and on the results of calculations using it.

For a deeper assessment of the metrological characteristics of the DM, it is necessary, at a minimum, to study the following factors:

(1) Evaluation of the influence of the computational algorithm parameters, including the adequacy of the applied physical laws (equations) and applied numerical methods. An example is the task of calculating mechanical stresses in structures, solved by the finite element method. One of the key parameters that determine the convergence (stability) of the solution is the grid structure of the partition of the simulated space into individual elements. Reducing the size of the elements increases the accuracy and stability of the solution, however, this increases the calculation time and the necessary computing power.

(2) Analysis of the influence of DM numerical coefficients errors on the calculation result. In the above example of calculating mechanical stresses by the finite element method, the values of elastic moduli (tensile, shear, and Poisson's ratio) and ultimate mechanical stresses (yield strength, tensile strength) are used as numerical coefficients. These values are taken from the reference literature or experimental data and have some uncertainty, and also may change over time depending on the operating conditions of the object.

(3) The study of the input data uncertainty influence. The data from sensors, testing devices and measuring systems used in the calculation model have some uncertainty. Evaluation of this uncertainty is a metrological task itself. At the same time, the metrological assessment of the digital twin involves an analysis of stability and reliability of the numerical solution, depending on the maximum possible errors of the sensors and measuring systems. In addition, the results of calculations using digital twins should be characterized by the uncertainty of the calculated value by analogy with the measuring transducers.
(4) An extremely important task of DM qualification for automatic control systems, including cyber-physical systems, is the study of the stability of their work in the event of distorted information or its absence due to malfunction of sensors or data transmission channels. Ignoring this part of the control procedure qualification has led, among other reasons, to known tragic accidents in aviation. The issues of ensuring the reliability of measurement information are discussed below.

3. Ensuring the Confidence of Measuring Data. Intelligent Sensors

Effective and safe use of control systems integrated in the CPS, distributed monitoring systems, as well as control and management systems based on DM is impossible without ensuring the confidence of the measuring data. The term "confidence," the authors understand the correspondence of the measured quantity value to the true value of the measuring quantity, adequately characterizing the object condition. A quantitative assessment of confidence can be considered as used in metrology «coverage probability», means probability that the set of true quantity values of a measurand is contained within a specified "coverage interval" [23]. A "coverage interval" can be derived from an expanded measurement uncertainty (GUM, 2.3.5) [24]. The coverage probability is also termed as "confidence level" in the GUM, C.2.29.

To ensure the reliability and confidence of the measurement data, it is necessary to ensure the state of metrological serviceability of the sensors, the correct (permissible) conditions for the measurements, as well as the transmission of data, eliminating their loss or unacceptable distortion. Generally accepted methods of periodic verification (calibration) for monitoring the sensors metrological serviceability are often not applicable for measurement tasks in Industry 4.0. For this purpose, it is necessary to eliminate the need for dismantling the sensors, as well as to provide continuous (frequent) monitoring of their performance. To solve this problem, the concept of so-called "Intelligent" sensors and measuring systems based on them was proposed.

The first sensor developments with the possibility of self-calibration were started in many organizations, including the Russian National D I Mendeleyev Institute for Metrology (VNIIM) in the early 80s of the last century [25]. In recent years, significant progress in this area has been observed in the methods development, standardization, and law regulation [26]. Previously, the development of self-calibration sensors was carried out mainly for use in specific areas, for example, for spacecraft and nuclear power facilities, which is often associated with the physical impossibility of dismantling and transportation for calibration and maintenance [27]. Now, the practice of integrating measuring instruments or sensors directly into the elements of technological equipment, structures, and products has become widespread. This creates, on the one hand, new markets for instrument manufacturers, and on the other hand, forces developers to re-think their minds on new approaches and concepts. Existing experience in intelligent sensors creating have allowed developing and approving three national standards of the Russian Federation [28–30].

In accordance with [28], "intelligent" is an adaptive (self-tuning) sensor with a metrological self-monitoring function. The term "adaptive" refers to a sensor, the parameters and/or algorithms of which during operation can vary depending on the signals of the transducers contained in it. Metrological self-monitoring of the sensor is an automatic check of the metrological serviceability of the sensor during its operation, carried out using the accepted reference value generated using the means built into the sensor (measuring transducer or measure) or the selected additional output signal parameter.

The smart sensor must have a digital output and transmit information on metrological serviceability through the interface. At the same time, having computing capabilities, an intelligent sensor allows to: *automatic correction* of the error resulted from influence quantities and/or aging of the components; *self-healing* in the event of a single defect in the sensor; *self-learning*.

Where:

- *self-healing* is understood as an automatic procedure for mitigating the metrological consequences of a defect, i.e., *fault tolerance* procedure;
- *fault tolerance* is understood as the ability to maintain metrological characteristics within acceptable limits when a single defect occurs;
- *self-learning* refers to the ability to automatically optimize parameters and work algorithms.

The development of intelligent sensors in the field of NDT is directly related to the concept of multi-parameter measurements mentioned above. Intelligent sensors are actively used in nondestructive testing [31]. In this regard, close interaction between metrologists and developers of NDT tools is necessary.

4. Standardization

The wide distribution and implementation of "smart" devices and "intelligent" sensors in the field of NDT makes it necessary to apply uniform methodological approaches and universal technical solutions. The adoption of relevant standards will increase the efficiency of the testing tools and monitoring systems development based on them, as well as simplify the choice for the consumer. The use of unified communication interfaces, data formats, and transmission protocol will make it possible to use equipment from various manufacturers to create distributed monitoring systems, as well as create systems with a flexible architecture that allows expanding the system coverage and increasing its functionality. To solve this problem, it is proposed to consider the following levels of standardization and individual issues to be standardized:

(1) Sensors:

Methodological and technical approaches to the development of "smart" and "intelligent" sensors. Currently, there is experience in developing such standards in the Russian Federation [28–30].

2. Testing devices:

- The format of the digital passport of the testing device, including, in particular: a unique identification number, type, and name of the device, name of the manufacturer, main technical characteristics.
- The format of the digital certificate of conformity (calibration certificate) [32].
- The standards developed for measuring instruments can be taken as the basis of these standards, while the features for NDT devices should be taken into account.

3. The format and transmission protocol for the primary information:

- The format for the presentation of measurement information, taking into account the specifics of various types of NDT
- Universal data transmission protocol.

4. Software and hardware platforms for data acquisition and processing:

- Universal formats for the acquisition and storage of information.
- Rules for the use of digital models for processing source data.
- Formats for placing data in the "cloud" storage.
- Information security requirements.

In the field of standardization, as the basis of unity of solutions, the practical elements of digitalization are becoming more and more interdisciplinary.

Certain results in this area have been achieved by international organizations, like IEEE SA [33], ISO, and IEC [34]. At the same time, the specifics of the NDT are not sufficiently taken into account in these developments. The international community of NDT experts in the person of the International Committee for Nondestructive Testing (ICNDT) should decide in which standardization organizations and in what format should cooperate in this area. International organizations for standardization (ISO, ASNT) are public structures and their members can make proposals for the development and approval of standards. This activity can be conducted by ICNDT members individually or in coordination with ICNDT. At the same time, it should be borne in mind that at present there are not enough qualified experts to develop such standards. Moreover, standardization processes often do not keep pace with the development of technologies, which leads to the fact that many leading companies quickly create enterprise standards, implement expert agreements, or dominate the market, sometimes using lock-in effects of their products and platforms.

A number of national committees (in Russia, the technical committee 371 “Non-destructive testing” of the Federal Agency for Technical Regulation and Metrology), regional societies (for example, Comité Européen de Normalization – CEN, American Society for Testing and Materials – ASTM), as well as the independent non-governmental International Organization for Standardization (Technical Committee 135 “Non-destructive testing”), which unites 165 countries in its ranks, are engaged in standardization in the field of NDT and CM. Within these structures, active work is underway to standardize NDT methods and technologies for their application, certification of personnel, and other issues. Note that a characteristic feature of modern standards is a new structure of their construction (three parts): a description of the NDT method as a multiparameter (with analysis of informative and interfering parameters), verification and calibration procedures, calculation of metrological characteristics that determine the need to provide reliable information as a key characteristic of NDT.

It should be noted the great role of technical committees on metrology (in particular, in Russia TC 206 “Standards and calibration charts” and a number of others) in the development of standards in the field of metrological support of measuring instruments, including in the field of NDT and CM. Recently held meetings and seminars of specialists from the American, British, Russian, German, Chinese, Canadian, and other NDT societies confirm that the developers and manufacturers of NDT and CM instruments, systems, and techniques should intensify the process of developing a system of international standards in the direction of “NDE 4.0” deeply integrated into the Industry 4.0 standardization system. This area is actively developing within the working groups, for example, Standardization Council Indusrtie 4.0 of the German Institute for Standardization – DIN. As one of the pioneers in this direction, it is worth highlighting the national standards developed in Russia [27–29] on terminology and the main provisions of intelligent sensors and systems, including the field of NDT and CM for cyber-physical systems and smart industries, which can be accepted as international. With the corresponding initiative, the Russian side is going to enter ISO.

Conclusion

The issues of standardization, metrological support, and methodological foundations for the development of intelligent NDT tools and CM systems in the context of the fourth industrial revolution challenges require the joint efforts of developers and equipment manufacturers, physicists, mathematicians, IT experts, metrologists, and standardization specialists. The solution of such complex tasks is possible on the basis of cooperation under the auspices of ICNDT and national NDT societies. Not only the commercial success of the NDT equipment manufacturers, but also the prospects for their existence depend on the success of this work. As Edwards Deming said, one of the founders of the modern theory of management: “It is not necessary to change. Survival is not mandatory.”

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Disclosure Statement

No potential conflict of interest was reported by the authors.

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