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Prospects and challenges of the Fourth Industrial Revolution for instrument engineering and metrology in the field of non-destructive testing and condition monitoring

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This article attempts to take a broad view of the current situation and trends in the development of instrument engineering and metrology from the point of view of the specifics of non-destructive testing (NDT) and condition monitoring (CM) in the context of the Fourth Industrial Revolution (4IR), a global restructuring of the socio-economic and industrial structure of the world economy. It presents the main technological directions of the Fourth Industrial Revolution, analyses the problems of the metrology and instrument-making industry and discusses the organisational and technical aspects.

Keywords: non-destructive testing, condition monitoring, Industry 4.0, digitalisation, Internet of Things, cyber-physical systems, smart sensors, digital models.

The main directions of the Fourth Industrial Revolution

'The Fourth Industrial Revolution (4IR)', better known as 'Industry 4.0', got its name from the 2011 initiative related to the need for broader use of information technology in production by turning businesses into 'smart' enterprises. However, the processes taking place in the modern world are no longer limited to the sphere of production. Fundamental changes are taking place in the energy, transport, healthcare and utilities sectors. Global tectonic processes are changing all lifestyle patterns, including the methods of interpersonal communication (social networks) and self-identification of each individual (replacement of a real person by a virtual image). A manifesto for the Fourth Industrial Revolution that provides a comprehensive representation of the concept is the work by Schwab[1].

It is inevitable that the measurement technology and metrology sector, as one of the structural components of the entire modern economy, is involved in the ongoing changes. Advances in the technologies for digital information generation, transmission, processing and storage (the processes commonly referred to as 'digitalisation') open up new opportunities for developers of measuring equipment and metrologists. Along with this, the introduction and development of 'smart' systems and digital models requires the direct participation of instrument makers and metrologists in the creation of 'intelligent' sensors and the development of fundamentally new approaches to ensure the metrological reliability of instruments and measurement techniques, including those in the field of non-destructive testing (NDT) and condition monitoring (CM).

The main directions of technical and technological breakthroughs in the modern world are given in the following sections.

Digitalisation

The development of technologies for the generation, transmission, processing and storage of digital information has led to an overwhelming percentage of information of man-made origin now existing in digital form. There are practically no analogue data transmission channels left and paper carriers of technical information will soon become an anachronism: drawings, electronic circuit and other technological documents are created, stored and used almost exclusively in electronic form. It is possible to consider that these changes have taken place naturally and do not require separate analysis and management. The current stage of digitalisation involves the creation of so-called digital platforms for managing processes and information flows in real time. Examples are electronic document management systems or decentralised taxi operators such as Uber. Another aspect of digitalisation is the development and application of digital models of various devices, processes and complex systems. Such modelling involves the creation of a digital (virtual) twin of a real object, which makes it possible to analyse its current state and the ongoing processes and predict its behaviour depending on changes in the operating conditions. The initial data are included in the model in accordance with the design or actual parameters of the object and later on the model is supplemented by data from condition monitoring, which makes it possible to adjust the model itself and predict the state of the object. Examples include a digital model of a car, used for virtual crash test simulation[2], as well as digital twins of complex engineering objects, which are used to calculate the conditions of load-bearing structures based on data received from a variety of sensors located inside and outside of the building structure.

The Internet of Things (IoT)

The authors understand the term 'Internet of Things (IoT)' as the ability of some devices and instruments to connect to the Internet,

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the transfer of information to an external recipient and the receipt of external orders. In the authors' opinion it is not quite correct to refer to such objects as 'smart', as the ability to exchange data does not imply the possibility of making independent decisions, but it makes it possible to automate the transfer of information to databases, include such devices in various hardware and robotic systems, use them to construct digital models and create cyber-physical systems (see below). Work is underway to standardise such devices in terms of their general characteristics, interface protocols and electronic data formats[3,4]. Modern communication technologies make it possible to easily connect any device to the Internet: the TCP/IP network protocol used in the Internet automatically assigns a unique IP address to the end-user upon connection, thus ensuring the user's unique identification in the network. As for the hardware connection, there are many types of network, both wired (Ethernet for example) and wireless (WiFi for example), and the development of cellular communication means that by using a very simple modem and a SIM card any device can connect to the Internet from any location where mobile coverage is available.

Cyber-physical systems (CPSs)

This is a complex of physical objects (devices, machines) and the computer systems that control them. A simple example of a CPS is a robotic production complex in which the production (set of physical operations) is carried out by robotic machines under the control of a computer (cybernetic system). Examples of such systems have been known about for a long time and, in the future, it is expected that global cyber-production will be created with the automation of all processes, from preparation of the production assignment to delivery to the end-user.

Smart systems

This concept combines the three already discussed: a digital platform for data flow control; a number of 'things' (sensors and actuators) connected to a network (the Internet); and a cyber-physical system, which controls the process on the basis of incoming information from the sensors by sending commands to the actuators. An example of a system that is really smart may be a power distribution grid (smart grid) with a variety of unstable energy sources (including solar panels, wind generators, etc) and a large number of consumers, which automatically regulates the processes of redistribution or accumulation of electricity from different sources depending on the level of consumption, while ensuring its quality and the metrological characteristics set[5].

As can be seen in the examples given, the instruments and technologies underlying the Fourth Industrial Revolution have been around for a long time and are widely used. From this point of view, it can be said that the revolution is happening right now. Therefore, the question that scientists and industry have to deal with is not how to prepare for the revolution but how to join the process right now and, possibly, how to influence its course.

The main trends in the development of NDT in the context of the Fourth Industrial Revolution

The authors believe that the main trend in the development of NDT methods and tools as measuring technologies is an active transition, at all levels of design, production and operation, from non-destructive testing to condition monitoring of products, engineering facilities, technological processes and environmental systems. In the field of metrology, the main directions are the development of metrological support for measuring transducers and non-destructive testing devices as a means of measuring multi-parametric and multi-dimensional quantities. The authors consider additive technologies to be one of the most promising applications for NDT methods.

The impact of 'digitalisation' on the existing infrastructure of instrument making and metrology

Transition from paper-based to digital document management and the recording of verification and calibration results in global information systems

The metrological infrastructure that ensures the unity of measurements includes several intersecting levels generating large information flows that require systematisation with the use of electronic information systems, for instance: reference standards of units; approved types of reference material and measuring instrument (MI); certified measurement methods; and information on the results of calibration.

Undoubtedly, the digitalisation of information flow has dramatically increased the possibilities in terms of searching for and retrieving the corresponding information. However, today they are basic email lists with the most primitive search and sorting options. It is impossible to use this information automatically for administrative or legal procedures. The very availability of such information in electronic form would enable significant automation of many processes. To meet this challenge, the German national metrology institute Physikalisch-Technische Bundesanstalt (PTB) has put forward an initiative for the development of a common European digital quality infrastructure for innovative products and services called the European Metrology Cloud. The developers need to design and create the following infrastructure elements: a trustworthy metrological core platform; reference architectures; technology-driven metrological support services; and data-driven metrological support services[6].

PTB is also working on the creation of a digital calibration certificate (DCS)[7]. The purpose of this development is to enable metrological organisations to use DCSs rather than their analogue counterparts. The machine-readable format of such DCSs is especially important for the digitalisation of production and quality control processes. The ultimate goal of the work is to develop universal formats for the DSC data exchange to be used in all sectors of metrology.

The obvious advantages of this approach are the following: reduction of the number of paper documents; prevention of false certificates being issued; and simplification of control over the timing of calibration.

There is a related trend for digitalisation of the operation and metrological certification of measuring instruments in the sphere of state regulation, which includes the provision of unique marks for all MIs and further MI equipment with the means to connect to a telecommunications network for the transmission of information to a single database. All of the technical solutions for this already exist, but it is necessary to create an appropriate information system, solve the problem of standardisation and make appropriate changes to the legislation.

The tasks of instrument engineering for the Fourth Industrial Revolution

Creation of measuring instruments that can connect to the Internet to perform data exchange (the Internet of MIs)

As was mentioned before, one of the urgent tasks for instrument makers is to provide MIs with communication equipment so that they can connect to the Internet. The introduction of such solutions will create prerequisites for the solution of tasks for the remote monitoring and collection of measurement information, the remote monitoring of technical conditions and metrological characteristics of measuring transducers and devices and the integration of MIs into 'smart' and distributed cyber-physical systems. In this respect, the authors see several levels of task for the construction of a hierarchical structure of the 'Internet of MIs':

- The hardware (physical) level of the Internet connection can be implemented on the basis of existing Ethernet, WiFi and mobile *n*G networks;
- The network protocol of the Internet, TCP/IP, is, in the authors' opinion, completely suitable for the set of tasks, as it is applied everywhere, provides unambiguous identification of the device by the assignment of a unique IP address and guarantees reliable information transfer;
- The applied (user-orientated) level of such a network has to be developed.

At the same time, it is necessary to solve at least the following tasks:

- Development and approval of a single universal format for MI data presentation (type, serial number, metrological characteristics, etc);
- Development and approval of the format for the presentation of measurement information (in addition to the measurement data, this may include such details as the time, GPS coordinates, environmental parameters, etc);
- Creation of a software platform for the exchange of data, as well as the collection and processing of information from MIs connected to the Internet.

These tasks are partly solved by the development and approval of international standards that determine the general characteristics of measuring transducers with interface modules, the functions of the interface modules, the format of the transducer data and the set of commands for configuring and controlling the interface modules, as well as for data reading and writing[3,4]. In addition, standards are being developed for the creation of networks of measuring transducers including, in particular, those for smart grids[8].

Creation of MIs adapted for use in robotic systems

Industrial automation/robotisation trends have gradually evolved into one of the main trends of Industry 4.0, *ie* the creation of cyber-physical systems. Measurement and control procedures are an integral part of any technological process and in automated unmanned production their importance increases a great deal. At the same time, automated systems are already being created for the non-destructive testing and condition monitoring of complex engineering facilities that are subject to a high degree of potential danger and entail a high level of responsibility, such as skyscrapers, power plants, bridges, pipelines, etc. MIs for these kinds of system should have some specific features that make them different from traditional devices, such as full automation of measurements and testing and calibration, increased reliability, the possibility of autonomous operation and integration into other systems, the availability of means of transmission of measurement information, etc. An example is an ultrasonic device for real-time spot welding quality control[9].

Development of universal sensors (primary measuring transducers) for 'smart' systems with the possibility of self-testing and remote calibration (verification)

Early developments in sensors with the possibility of self-testing were made by many organisations, including the D I Mendeleyev Institute for Metrology in the early 1980s. Significant progress has been achieved in this area recently in terms of the development of methods, standardisation and regulation[10,11]. Previously, the development of self-testing sensors was mainly aimed at their use in specific sectors, for example in spacecraft and nuclear power facilities, which is often related to the fact that it is physically impossible to dismantle the devices and transport them for periodic calibration and maintenance[12]. Nowadays, the practice of integration of measuring instruments or primary measuring transducers directly into the elements of technological equipment, structures and products has become widespread. On the one hand, this creates new markets for instrument makers and, on the other hand, forces developers to restructure their thinking and shift towards new approaches and concepts[11,13-15]. Existing developments in the field of smart sensors have made it possible to develop and approve two standards of the Russian Federation[16,17]. In[16], a smart sensor is defined as 'an adaptive sensor with the function of metrological self-control, which has a digital output and provides the transmission of primary measurement information and information about proper metrological functionality through the interface'. At the same time, a smart sensor with computational capabilities makes it possible to perform the following tasks:

- Automatic correction of errors resulting from exposure to influencing quantities and/or ageing of components;
- Self-repair in the case of a single defect in the sensor; and
- Self-learning.

In accordance with[17], metrological self-control methods for measuring transducers and measuring systems are classified into direct metrological control methods and metrological diagnostic self-control methods.

Pronin *et al*[18] believe that the most promising form of metrological diagnostic self-control is the type that tracks the deviations of the diagnostic parameter characterising the critical component of the error from the reference value of the parameter set during calibration. Critical refers to a component that is dominant or tends to grow rapidly. Metrological diagnostic self-control is based on the results of a special metrological analysis of the sources of error typical of the operation process. These include, for example, the ageing of materials, defects caused by violations of MI manufacturing technology that have only become apparent after some time, etc.

Digital industry establishment

Digitalisation of industry, which provides the basis for the Fourth Industrial Revolution, is the integration of measurement results obtained with the use of a network of measuring transducers and other sources of information into a single whole and their processing with smart machine algorithms for automated process control and decision-making for the implementation of the global business-to-business (B2B) idea. Based on these technologies, non-destructive testing that is now applied to finished products at the final stage may be replaced in the future by an operational interrelated analysis of data between the manufacturer and its customers, for optimisation and flexible operational changes in the required parameters of products at each stage of their manufacture, including taking due account of customers' requirements[19].

The key to the implementation of this concept is a 'digital twin' entity, which is the basis for the vast majority of modern practical digital applications for physical objects (from technological processes and production lines to entire enterprises), as well as for the factories of the future, production environments with automated decision-making and control based on large flows of digital information, with the option of intelligent machine learning.

In the field of standardisation as the basis of the universal solutions, one of the main tasks is related to the fact that the practical elements of digitalisation are becoming more interdisciplinary. It must be decided which standardisation organisations will develop standards in this area, but it should be borne in mind that there are currently virtually no qualified experts for the development of such standards. Moreover, standardisation processes do not often keep up with the development of technologies, which is why many leading companies quickly create enterprise standards, implement expert agreements or dominate the market, sometimes using the lock-in effects of their products and platforms (similar to Apple).

The tasks of metrology for the Fourth Industrial Revolution

Development, standardisation and legislative approval of new principles for metrological support of smart sensor distributed networks

Within the framework of the processes under consideration, metrologists face the tasks of development, standardisation and legislative approval of new principles for metrological support of smart sensors in information and measurement systems.

The use of sensor networks instead of single measurement tools, in combination with large datasets, cloud computing and remote services, poses a number of new requirements for metrology. For example, calibration of the sensor network must take into account the measurement possibilities of individual transducers, communication issues and approaches to aggregated data. In some areas of production, such as unified power systems, the first developments have been successfully implemented, but much more research needs to be carried out to establish harmonised communication with sensor networks. The methods of calibration and measurement required for remote services are completely different. For example, online and remote measurements of environmental parameters, such as air or water quality, have different calibration requirements in terms of the repeatability, reproducibility and overall assessment of the measurement results[20].

The development of high-frequency data transmission technologies and their use for distributed networks of measuring transducers results in stricter requirements for the reliability of data transmission. In this case, the technology of virtual measurements or simulations of measuring devices should be considered as the measuring instruments and appropriate metrological maintenance must be applied to them. Thus, in the future, traceable calibration (verification) for virtual measurements and calculation of measurement uncertainties in modelling must be provided in the structure of the hierarchy scheme of the traceability chain.

Development of principles of metrological support for control algorithms and decision-making based on measurement information

Standardisation and legal metrology of non-destructive testing and condition monitoring, which are needed to ensure confidence in the measurement results, must also undergo changes in the conditions of the Fourth Industrial Revolution. The main trend will be an increase in the use of distributed measurements and remote data processing. That is, the structural elements of measurement systems, in general, will be distributed over long distances in different regions or even countries[21]. An example could be a primary measuring piezoelectric transducer with a network interface for wireless transmission of primary measurement information to the cloud infrastructure, where a virtual device in the form of a software module performs a secondary transformation of measurement information and calculates the measurement result. This could be transmitted and shown to the operator, used for further processing, storage and management or transferred to the services responsible for the technical condition of the object under control (during operation) and used for the technological process of its manufacture. In this context, the designers could use the cloud infrastructure in question for remote updating of the software and remote adjustment of the calibration (verification) parameters. For legal metrology, the implementation of these tasks is currently difficult, because in the assessment of the compliance of the metrological characteristics of a measuring instrument in the form of a distributed software and hardware environment it is necessary to take into account the parameters of communication systems, software, cloud computing, etc. On the other hand, there will be an urgent problem in terms of revising the principles of configuration, calibration and verification of distributed measuring instruments, because a cloud server is nearly inaccessible to experts and the software can be proprietary rather than open, possibly without the opportunity to test the communication on the site.

Metrological support of digital models

One of the key provisions underlying the development of new measuring instruments (which will be designed based upon the principles outlined above) is the need to take into account the fact that promising programmes that will allow for the creation of digital models of distributed measuring instruments and objects of control and the calculation of controlled parameters for them and the parameters for the reliability of objects, as well as the digital models themselves, have a number of limitations, including the following factors:

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

Incorrect application of physical models and mathematical methods for calculation of the parameters of digital models, as well as inaccuracies or errors in the setting of physical parameters, can lead to erroneous results in the prediction of the properties and the behaviour of real objects. In the context of a broad introduction of digital models, it is necessary, for the purposes of prediction of the future behaviour and decision-making in relation to potentially dangerous objects, to take measures for the prevention of their uncontrolled and improper use. This will require the creation of an organisational and legal system and engineering infrastructure for determination of the completeness and adequacy of digital models (verification), establishment of restrictions on their applicability (validation) and control over the correct application of digital models in real-life conditions. In particular, a digital model authorised for use in critical or potentially hazardous areas will have to undergo some form of *in-situ* testing. The use of such a model for the creation and control of a real object will have to be made by qualified (certified) specialists responsible for the correct application of the model and the proper presentation of the parameters of the object of control.

At present, there are no universally accepted established approaches for the assessment of the quality of digital models of the 'measuring instrument/object of control'. For practical applications, a kind of 'metrological support' for digital models needs to be developed to determine the following parameters:

- The accuracy and uncertainty of calculations (measurements);
- The influence of uncertainty in the input data on the results of calculations of the controlled parameters; and
- The stability of the model in the case of different combinations of input data and various interfering parameters.

In the long run, it may become necessary, for the widespread adoption of digital models in areas related to technical and energy security and other areas of government regulation, to establish a public system that provides for the following:

- Digital model testing;
- Maintainence of a digital model register; and
- Certification of personnel and accreditation of organisations for the right to use digital models for forecasting and management of real-life objects and processes.

Prospects and problems related to the Fourth Industrial Revolution for the NDT and CM sphere

All of the above prospects and challenges are directly related to the sphere of non-destructive testing. At the same time, it is necessary to emphasise certain aspects that are specific to this area or have an exceptional impact on the ongoing processes.

From non-destructive testing to condition monitoring

First of all, it is necessary to note the trend of the transition from classical non-destructive testing, localised in terms of time and space, to condition monitoring. The essence of this process is the creation of automated information/measurement systems that can operate in a continuous mode without direct human intervention, analysing the measurement information on the basis of digital models of controlled objects and measuring instruments and ultimately developing management recommendations and solutions based on the processing of data. This definition implies the following tasks:

- Development and production of self-calibrating measuring transducers with an extended service life;
- Creation of equipment for automated non-destructive inspection, connected to telecommunication networks with the use of standardised protocols through a universal hardware and software platform;
- Development of digital models of objects of non-destructive testing, including models of defects to be determined by non-destructive testing methods;
- Development of digital models of measuring instruments in the field of non-destructive testing; and
- Development of algorithms for the automatic processing of measurement information based on digital models of objects and non-destructive testing for immediate decision-making.

Metrological support of non-destructive testing devices as the means of measurement of multi-variable (multi-dimensional) quantities

Most measurement techniques for non-destructive testing are multi-dimensional and multi-variable. For example, in the widespread application of the eddy current method for measuring the thickness of coatings, the readings of the device depend not only on the geometric dimensions of the coating but also on the properties of the coating materials and the base (substrate), including electrical conductivity, magnetic permeability, density, etc[22]. A large number of factors have an impact upon the results of mechanical stress measurements such as the geometry of the controlled object and its location in space (multi-dimensionality), as well as its electrical, magnetic and mechanical properties (multi-parameter nature).

Automated measurements require automatic adaptation of the sensors in response to changes in the properties of the controlled object. This problem is solved by the development of multi-parameter sensors, which make it possible to take into account the main factors that affect the measurement result.

Non-destructive testing in additive technologies

A separate scientific and technical task is the development of tools and methods of non-destructive quality control for products manufactured using 3D printing. Currently, additive technologies are increasingly being transferred from the modelling stage to actual production processes. In this regard, the issues of non-destructive testing of products manufactured on 3D printers are becoming extremely relevant. The complexity here lies both in the specific physical and mechanical properties of the materials used and in the complex structure of the product associated with the manufacturing technology. In particular, such materials are extremely difficult to inspect using ultrasonic methods.

Conclusion

The Fourth Industrial Revolution is not some abstract future but a practical process that is taking place right now, affecting all spheres of human life. We can enjoy its fruits, and, at the same time, we must take part in it in the most effective manner. The commercial success of instrument making companies and the demand for the services of metrological organisations directly depend on how their work meets the new requirements. This was most succinctly expressed by Edwards Deming, one of the founders of the modern theory of management, who said: "It is not necessary to change. Survival is not mandatory."

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The temperature of the core of the stirring tool was obtained. Compared with the experimental measurement results, the accuracy of the temperature measurement model in the core area of the stirring tool was verified.

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