NDE 4.0 IS A PARADOXICAL SUMMARY OF A DECADE

Vladimir A. Syasko
Russian Society for Non-Destructive Testing and Technical Diagnostics
+7 921 9334343
E-mail: 9334343@gmail.com

Abstract

In November 2011, the government and business circles of Germany adopted the strategic initiative INDUSTRIE 4.0, aimed at the development of industrial information technologies as the basis of the modern economy. The English-language "INDUSTRY 4.0" and the number "4.0" itself have become global trends/brands. The need to integrate methods, technologies and equipment into "smart" distributed processes of design, production and maintenance of products has formed a new area of knowledge of NDE 4.0. Ten years of research and development have passed. The problems are identified, largely related to the lack of a properly formulated strategy and unity of goals of the specialists involved in the process of various industries and understanding of NDE 4.0 as an interdisciplinary scientific and technical direction aimed at building networks of connected intelligent sensors forming large systems embedded in the infrastructure of distributed "smart" enterprises/productions, the development of related engineering disciplines as the basis for ensuring autonomous long-term functioning of these systems based on realistic models of NDT and CM tools, embedded in robotic complexes using deep/machine learning with the subsequent implementation of the principles of artificial intelligence in NC, MS, etc., taking into account the trends of INDUSTRY 4.0, as well as solving problems related to the transition from automated to automatic NDT and CM within the full life cycle of complex technical systems.

The article analyzes the main tasks and forecasts in the field of development of methods, equipment and technologies of NDT and CM in time intervals of 5, 10 and 25 years, their relationship with the goals and objectives of the INDUSTRIE 4.0 initiative. Also formulated general technical tasks, the solution of which will be the basis for practical implementation of these goals. Examples of achievements of individual corporations and firms in the development of NDT systems for "smart" factories are given. In conclusion, the problems of integration of INDUSTRY 4.0 and NDE 4.0 and ways to solve them are analyzed.

1. Introduction. INDUSTRIE 4.0 AND/OR INDUSTRY 4.0

In November 2011, the German government adopted the strategic initiative INDUSTRIE 4.0, initiated in February of the same year, a project of integrated digitalization of industrial production with the aim of better equipping it for the future, which in its essence is a strategic initiative to develop primarily machine–building

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production as the basis of the modern economy. Industrial production should absorb modern information and communication technologies like a sponge. The technical basis for this will be intelligent systems integrated into a single digital network. With their help, self-organized production should become as possible as possible: people, machines, systems, logistics and products will communicate and interact directly with each other. Networking should make it possible to optimize not only individual stages of production, but also the entire value chain. The network should also cover all stages of the product lifecycle — from product idea, development, production, use and maintenance - to processing. Production processes should be built on the basis of a single information space that allows, in the future, the elements of production systems and systems as a whole to interact with each other without human participation, relying on the "ubiquitous" and mobile Internet, miniature production devices (cyber-physical systems), artificial intelligence and learning machines [1].

Ten years have passed, it has already been forgotten that this is a national project of one particular country. The English-language "INDUSTRY 4.0" and the number 4.0 itself have become global trends.

Traditionally, the concept of INDUSTRY 4.0 (INDUSTRIE 4.0) is closely associated with the fourth industrial revolution, the onset of which was announced by the founder and president of the World Economic Forum in Davos Klaus Schwab in early 2016.

It should be noted that it was in Germany that they decided to combine these areas into one package and call it a "revolution". Unlike the three previous industrial revolutions, the fourth one was started man-made, "from above", within the framework of one country.

In Germany, they approached the matter slowly and thoroughly. In January 2011, the project was initiated, and at the Hanover Exhibition of the same year, the concept of the fourth Industrial Revolution was presented to the general public. In November, the Industry 4.0 project was adopted by the German government as part of the High-Tech Strategy 2020 plan. In April 2013, the German industrial unions BITKOM, VDMA and ZVEI, uniting about 5 thousand companies, founded the Industry 4.0 Platform [2]. With the support of the platform, self-organizing working groups on various aspects of the project implementation began to operate. In April 2014 The INDUSTRIE 4.0 platform has published the first version of the reference architecture model for INDUSTRIE 4.0 - Referenzarchitekturmodell fur Industrie — RAMI 4.0 [3], the purpose of which is to describe complex relationships and decompose them into "convenient" fragments. New DIN standards are being created for the new architecture. On April 14, 2015, the project deployment strategy was published with interim dates for each section until 2020.

In recent years, similar innovations have become widespread in other industrialized countries. In the USA, this initiative originated under the name "Industrial Internet Consortium", or IIC for short. The Industrial Internet Consortium was founded in March 2014 by AT&T, Cisco, General Electric, IBM and Intel. This is a non-profit organization, which by the beginning of 2016 had already grown to more than 200 members, among the participants are also non-American companies. In Japan, there are initiatives called the "Industrial Value Chain Initiative", or IVI for short. The initiators are large Japanese companies. In the 2015 five-year plan, China also launched initiatives similar to the German platform “industry 4.0”. They should significantly support the desired transition from a low-wage country to a global industrial power. South Korea is investing in so-called smart factories. In some European countries, there are other activities comparable to the INDUSTRY 4.0 platform, for example, in France under the name: "Industrie du futur".

The fourth stage of the revolutionary transformations in industry and, possibly, in the social sphere that we are currently experiencing is based on the following four key areas of activity:

- the wide (pervasive) spread of the Internet and the connection to it of a wide variety of inanimate objects (Internet things) equipped with a wired or wireless standardized communication channel with an information and communication network and a worldwide system of unified computer networks for storing and transmitting information;
- intensive development of the concept of cyber-physical systems - an information technology concept implying the integration of computing resources into physical entities of any kind, including biological and man-made objects (Fig. 1);
- development and implementation of the principles of building smart factories - the most intensive and comprehensive use of network information technologies and cyber-physical systems at all stages of product production and delivery - value creation (Fig. 2 and 3);
- active use of digital doubles – digital copies of physical objects and/or processes;
- adaptation of the ideas of artificial intelligence and deep machine learning based on the theory of artificial neural networks, applied to production processes and technologies.

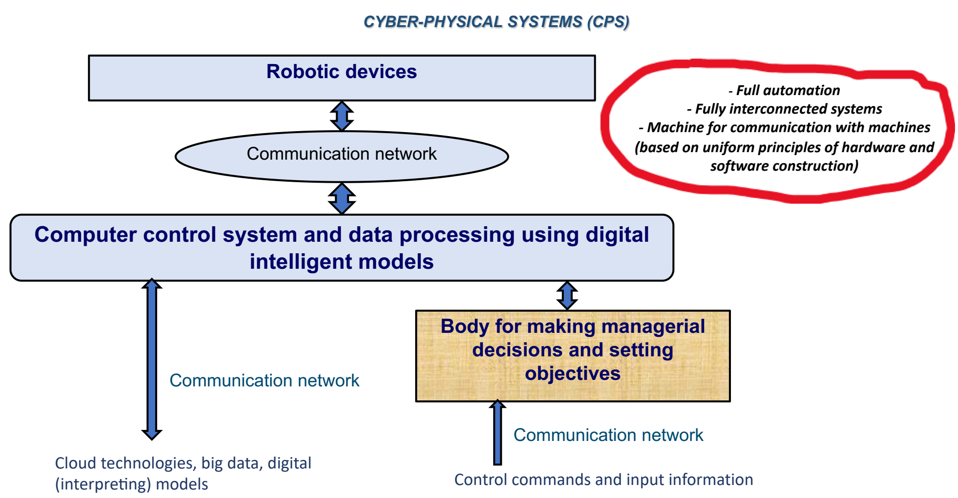


Figure 1. Generalized structure of the cyber-physical system of industrial productions

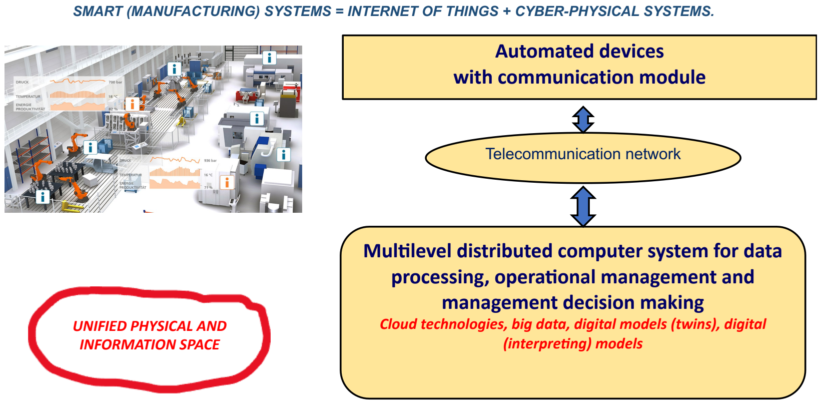


Figure 2. Smart manufacturing system

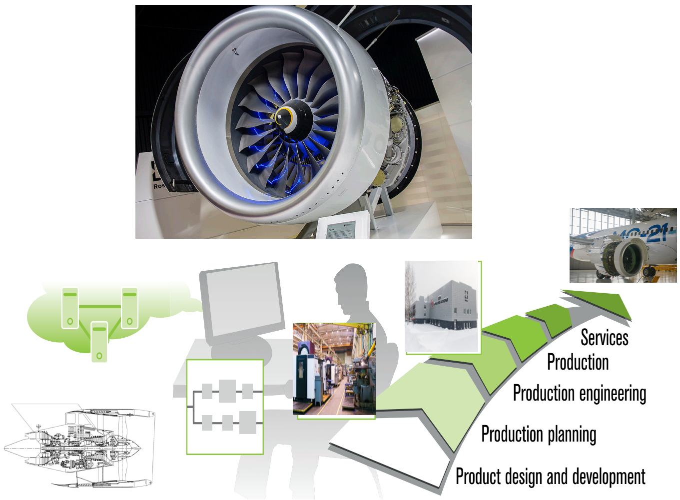


Figure 3. Digital end-to-end engineering across the entire value chain of both the product and the associated manufacturing system ("digital factory" for production of pd-14 aircraft engines for MS 21 aircraft)

The authors of the project have convinced and continue to convince that we are at the origins of fundamental changes, the scale and consequences of the fourth industrial revolution are radically different from all previous ones and humanity will see stunning technological breakthroughs.

2. NDE 4.0

The idea of enhanced integration of cyber-physical systems into production processes, starting from the stages of designing high-tech products and designing/configuring smart factories themselves, on the basis of a single information and physical space, allowing, in the future, elements of distributed production systems and systems as a whole to interact with each other without human intervention, that is, completely automatically, inevitably captured and specialists in the field of methods, devices and technologies of non-destructive testing. The objective necessity of embedding NDT methods, technologies and equipment into smart distributed processes of design, production and maintenance of products has formed a new interdisciplinary scientific and technical direction NDE 4.0 as a field of knowledge about physical methods and devices for detecting inhomogeneities of materials and products, as well as determining their geometric and physic-mechanical characteristics, in order to quantify the structural integrity and compliance with the specified design parameters using the basic technical ideas and principles of the organization of smart factories - INDUSTRY 4.0, (including uniform principles of standardization and metrological support). The purpose of the development of this direction is to build networks of connected intelligent sensors that form large systems embedded in the infrastructure of distributed "smart" enterprises/ industries, the development of related engineering disciplines as the basis for ensuring the autonomous long-term functioning of these systems based on realistic models of NDT and CM tools embedded in robotic systems using deep/machine learning, followed by implementation of the principles of artificial intelligence in NDT and CM, taking into account the trends of INDUSTRY 4.0, as well as solving problems, associated with the transition from automated to automatic NDT and CM within the full life cycle of complex technical systems and high-tech products.

The key idea is the embedding of NDT tools and technologies into cyber-physical systems and distributed smart factories based on the implementation of the strategy – the implementation of the principles of organizing a single physical and informative space, which allows, among other things, to practically consider the use of contactless NDT methods in in-line high-tech production. This allows us to identify a group of terms and directions that combine into a single whole processes in within the framework of INDUSTRY 4.0 and NDE 4.0 (fig. 4) by adapting technologies and knowledge of related scientific and technical fields (for example, metrology, standardization, microelectronics, physics, materials science and many others)

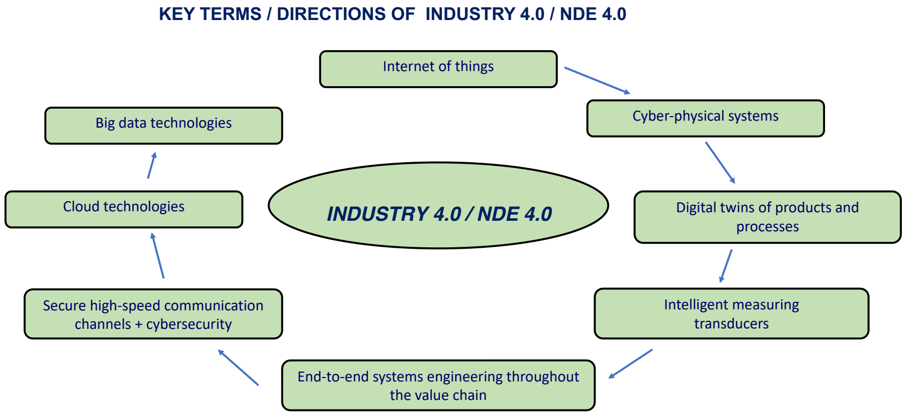


Figure 4. Terms and areas of activity that are common to the processes within INDUSTRY 4.0 and NDE 4.0

Ensuring the above-mentioned goals and principles in the design and construction of structural elements of smart manufacturing and smart manufacturing in general requires a change in the structure of measuring transducers and NDT tools in general, taking into account the fact that they actually have to be multiparametric measuring tools that provide metrologically reliable information about the controlled parameters while suppressing interfering factors. This involves the use of intelligent converters – additive sensors with metrological self-monitoring functions [4], the structure of which in the cyber-physical system and smart manufacturing as a whole, as well as the functions provided (performed) are shown in Fig. 5.

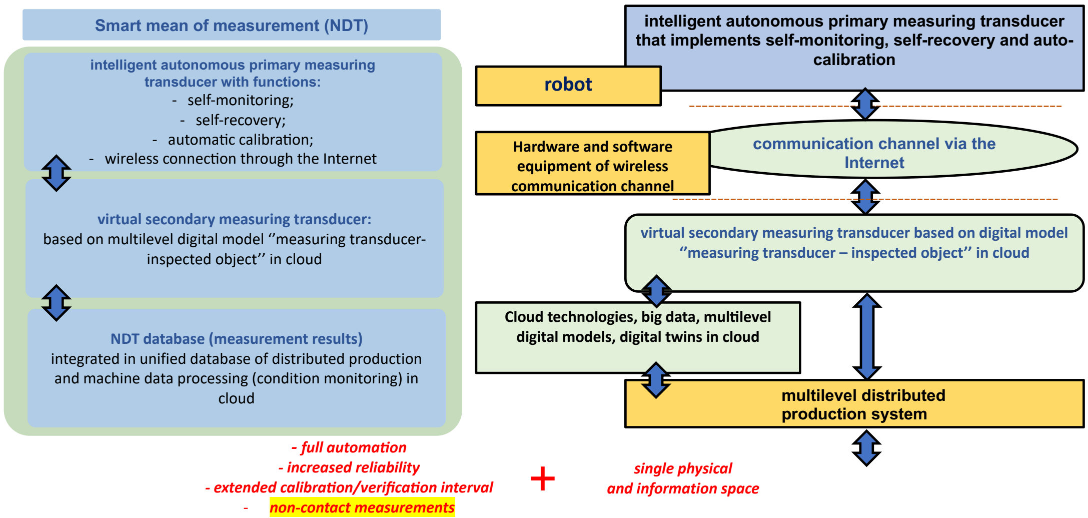


Figure 5. Structure of perspective intelligent measuring transducers and their linking with CPS of smart factories

It should also be borne in mind that developers of NDT tools should participate at all stages of creating smart factories within the framework of compliance with uniform principles of structuring and design, as well as ensuring the reliability of the information received and reliability in making management decisions. The development of a product, process and technology for its manufacture, service and NDT and CM systems is a single whole, based on the unified principles of standardization and metrological provision (Fig. 6).

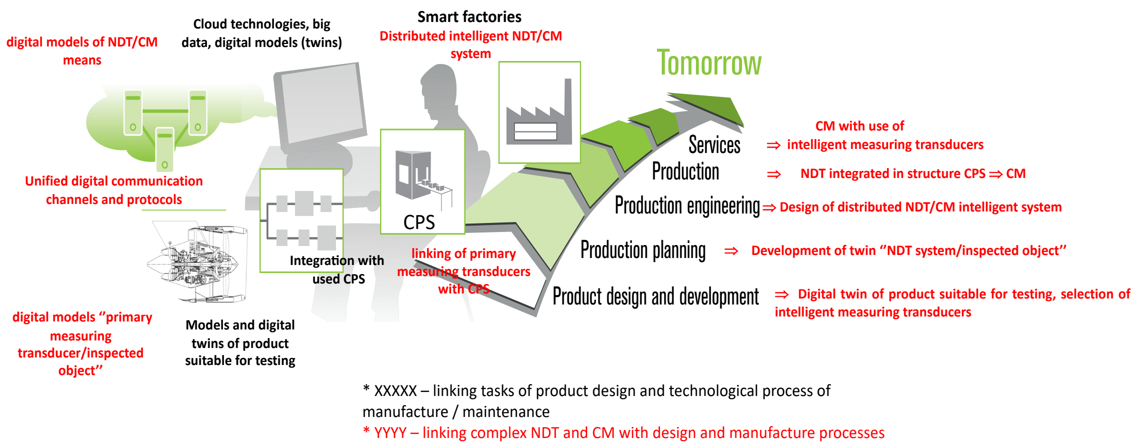


Figure 6. Integration of NDT and CM systems into a unified digital chain of product development implementing principledigital end-to-end engineering across the entire value chain of both the product and the associated manufacturing system

In addition to the developments of individual specialists, universities and enterprises, working groups and research centers have been created in a number of countries on the initiative of national and interstate public organizations, whose task is to develop and subsequently support a collective view of future requirements for NDT in advanced industries, as well as the formation of an appropriate list of proposals for industrial and government structures that ensure achieving a synergistic effect at the intersectoral, national and international levels, ultimately aimed at ensuring security and improving the well-being of the population.

In Germany, the structure of the German Society for Non-Destructive Testing has identified the direction of NDE 4.0, which includes the work of four working groups:

- additive manufacturing;
- interfaces for data transmission and data storage;
- human-machine interaction;
- machine learning.

In the UK, a Research Centre in NDE (RCNDE) was established with the participation of BINDT as a leading scientific and industrial association carrying out industrially significant research in the field of NDT and structural condition monitoring of structures, uniting more than 50 organizations representing aerospace, electric and nuclear power, oil and gas industry, defense and industrial sectors.

ICNDT and EFNDT have also organized working groups that include representatives of most national societies.

3. NDE 4.0: KEY GOALS (OBJECTIVES) AND FORECASTS

One of the tasks of the working groups and research centers was to develop some views on the requirements for the actual technologies and means of NDT and CM for the near (5 years), medium (10 years) and long (25 years) perspective, taking into account the involvement in the processes taking place in the industry of the leading world powers. Summarizing the published studies conducted since about 2010, allows us to highlight the tasks, forecasts and activities presented below, taking into account individual industry trends, technological opportunities, innovations, future industry needs and needs of companies, market, regulatory, environmental and economic factors, as well as the safety factor, made for the period, approximately 2012 – 2045 Tasks and forecasts indicated new (required) opportunities of the NDT, as well as new industrial priorities focused on these opportunities, and vice versa.

Generalized tasks and forecasts included:

- tasks and forecasts of the development of new NDT and CM technologies: control of composite materials, functional coatings, printed materials, determination of defect characteristics and sensitivity of control, contactless control, etc.;
- tasks and forecasts in the field of the structure of controls of materials and products in production and operation: multi-parameter automatic control, modeling of the control process and data collection, etc;
- tasks and forecasts of technological control in the production of products: self-testing and self-diagnosis of NDT tools, condition monitoring throughout the life cycle, machine learning, evaluation and forecasting of reliability indicators of products, etc.

Table 1. Key tasks and forecasts in the field of NDT and CM for 5, 10 and 25 years.

After 5 years	After 10 years	After 25 years
New in testing technology		
- using the theory of materials science to increase the reliability of detection and determination of defect characteristics	- systems for modeling NDT methods and technologies	- NDT of products made of any materials with a full 3D representation of the structure
- control of objects of complex geometry, including multi-layered with a complex internal structure and previously unsuitable	- physical models "measuring converter-object of control" and the use of probabilistic approach in detecting defects (PoD)	- fast, non-contact NDT of large areas and at long distances by sensors without mechanical scanning
- reduction of the volume or complete elimination of manual control, followed by replacement with a robotic NDT	- a single data format, standardized data transmission protocols, compression of the volume of stored data	- construction of models taking into account the real properties of the materials used to assess the condition of structures
- the use of manipulators with permanently installed or built-in sensors, the use of local monitoring systems	- distributed networks of measuring transducers	- creation of a "digital double" of an object to assess the condition of structures during the life cycle.
- complication of computational models with subsequent experimental verification;	- automatic adaptation to the characteristics of the material, multi-parameter control to suppress interfering parameters	- functional compatibility of NDT and monitoring systems, full automation of data processing
- real-time collaborative data processing	- measurement of mechanical characteristics of materials	- implementation of artificial intelligence systems
- reliable automatic interpretation of control results	- universal autonomous adaptable equipment for remote NDT	- biological sensors
	- automatic online data processing, assistance to the operator in decision-making - automatic NDT using remote access	
New in the structure of testing for materials and products		
- minimizing the amount of manual control - widespread use of robots and manipulators for NDT and CM operated equipment, especially when access is restricted or in adverse conditions	- expansion of monitoring and screening areas at large-area facilities	- full equipment of plants with NDT systems with a range of 10-100km
- the use of durable, reliable, permanently installed sensors integrated into distributed networks to monitor the development of defects	-automatic self-calibrating sensors with extended service life -transition from non-destructive testing to condition monitoring	- self-monitoring methods for production structures, "smart" systems of non-destructive testing and condition monitoring

Table 1 continued on the next page.

Table 1. (Continued)
Key tasks and forecasts in the field of NDT and CM for 5, 10 and 25 years.

- local condition monitoring systems in critical inaccessible areas of operated products	- a wide range of universal platforms for remote and automated productive NDT (crawlers, UAVs, etc.)	- integration of monitoring and NDT systems into the structure of a smart enterprise to obtain complete information about its condition and optimize its functioning
New in technological testing in the production of products		
- development of technological monitoring of production processes (for metal and non-metal products)	- on-line tomography of products manufactured using additive technologies	- development of materials convenient for NDT
- NDT for products manufactured using additive technologies	- operational technological NDT in the production process, replacing the output control	- design of equipment/products taking into account the controllability
- high-precision robotic NDT for extended/large-sized objects of complex shape		- comprehensive product evaluation, in which the quality of each of the components should provide predictable performance characteristics
		- full monitoring of the production cycle from the workpiece to the buyer
		- conducting NDT without increasing the duration of the production cycle

Tasks and forecasts in terms of methods, tools and technologies for obtaining measurement information are highlighted in green, red – in terms of the development of NDT automation hardware, blue – software and hardware for collecting and processing measurement information, as well as decision-making.

The key to the generalized first five-year forecast was that the achievements in the field of methods, tools and technologies of NDT, focused on use in automated production, will allow to switch to the use of high-precision high-speed robotic NC, performed contactless in the local physical and informative space of the object of control, meeting the requirements of short-term business planning of individual enterprises, as well as the definition of the needs of the NDT business that must be addressed at subsequent planning stages.

The ten-year generalized forecast concerns the development of promising technologies as a kind of springboard for the transition to unpopulated (automatic) NDT technologies as part of distributed smart industries. At the same time, it is characteristic that the needs relate not to individual enterprises, but to a group of related industries, requiring the organization of free access to the use of NDT data and overcoming the current restrictions in terms of security. According to the forecast, the key should be the development of high-performance networks of intelligent measuring transducers and information processing tools using multilevel modeling as the basis for condition monitoring of high-tech facilities requiring the use of distributed intelligent measuring transducers, possibly built on one of the unified bases and used in the manufacturing process.

For a twenty-five-year forecast, the key, in fact, is to move away from destructive testing (testing), subject to the development of non-destructive testing as an interdisciplinary direction and a total transition to condition monitoring as the basis for the quality and operability of products, as well as monitoring the technological cycle of production itself, subject to fully automatic processing of results and decision-making at all levels using adequate models, including when communicating with cyber-physical systems embedded in the process. At the same time, the time spent on the NC will not increase the production cycle. Contactless measurements in a single information and physical space with the use of fundamentally new controllable materials should become a reality.

The fundamental points that ensure the implementation of the tasks listed in Table 1 in the context of solving similar tasks within the framework of the INDUSTRIE 4.0 initiative, in addition to the actual development of NDT as an interdisciplinary direction, are: ensuring the reliability, and possibly redundancy, of multiparametric primary measurement information, guaranteed adequacy of product counterparts, NDT tools and models "multiparametric measuring converter – the object of control", as well as the confirmed qualifications of users, which can only be guaranteed by an appropriate system of metrological support and standardization, which allows to implement the unity of approaches in the construction of measuring transducers and distributed networks, communication channels and data formats within the unity of terms and definitions.

It is also necessary to identify general technical tasks, the solution of which will be the basis for the practical implementation of the above goals:
1) Development of basic principles for the construction and implementation of autonomous single-crystal (single-body) intelligent primary measuring transducers for "smart" distributed systems with the possibility of self-testing and remote calibration (verification), providing:
- automatic correction of the error resulting from the influence of interfering parameters and/or aging of components;
- self-repair in case of a single defect in the sensor;
- self-study using digital models in the cloud space;
- transmission of information via wireless high-speed digital communication channels.
2) Providing a systematic approach to measurements in the field of NDT as multiparametric, taking into account the influence of controlled and interfering parameters on the measurement results.
3) Development, standardization and legislative approval of new principles of metrological support of distributed networks of intelligent measuring transducers:
- ensuring the traceability of measurement information obtained during control procedures to primary standards that ensure the unity and reliability of the source data for monitoring and control systems;
- ensuring the adequacy of procedures for self-monitoring and self-calibration of primary measuring transducers (intelligent sensors);

- metrological support and verification of methods of interpretation of the received data, including digital models of distributed NDT systems;
- metrological support and validation of calculation models (digital doubles) of control objects;
- certification of control methods based on complex tests on real objects or control samples.

4) Equipping autonomous measuring instruments (SI) with wireless communication equipment for connecting via the Internet to a single cloud space
- development and approval (standardization) of the format for the presentation of measurement information;
- creation of a hardware and software platform (platforms) for data exchange, as well as the collection and processing of information from measuring instruments connected to the Internet (a single cloud space);
- development and approval of a single universal format for the presentation of data about the measuring instrument (type, serial number, metrological characteristics, etc.)

6) Development and approval of a unified approach to the construction of software and hardware platforms for data collection and processing in terms of:
- universal formats for collecting and storing information;
- rules for using digital models for processing source data;
- the format of data placement in "cloud" storage;
- information protection requirements

7) Development of a metrological support system for multi-level digital models (including cloud) of distributed autonomous measuring instruments (intelligent sensors) and monitoring objects for calculating controlled parameters and reliability parameters of objects that guarantee:
- adequacy and completeness of the physical models used;
- applicability of the mathematical methods used;
- the accuracy of setting the parameters of the simulated objects and the boundary conditions of their application.
- testing of digital models when approving the type of measuring transducers;
- the ability to maintain a register of digital models;
- the possibility of personnel certification and accreditation of organizations for the right to use digital models for forecasting and management of real objects and processes.

8) Creation of an organizational and legal system and engineering and technical infrastructure to establish the completeness and adequacy of digital models (verification), establish restrictions on their applicability (validation), as well as control over the correctness of the use of digital models in real conditions.

4. NDE 4.0. Examples of achievements

A number of concerns trying to locally implement the main ideas of the strategic initiative, based on the identified development directions (Fig.1) within the framework of accepted terms and definitions common to INDUSTRY 4.0 and NDE 4.0, have designed and manufactured enterprises or production sites that can generally be classified as smart factories with a single physical and information space, based on cyber-physical systems using digital counterparts of products, with built-in systems of contact or non-contact non-destructive testing and condition monitoring of products and the manufacturing processes themselves, implementing together the principles of "digital end-to-end engineering across the entire value chain of both the product and the associated manufacturing system" (Fig. 6).

BMW Concern has developed an automatic production line with an integrated 3D X-ray tomography system for complex metal parts for the automotive and aircraft industry, meeting most of the signs of smart manufacturing and trends of INDUSTRY 4.0 and NDE 4.0. Distinctive features of the production line integrated with the control system within a single physical and information space:
- virtual model "NDT system - control object" for all controlled parts;
- automatic processes of results processing (large data arrays) and decision-making based on control results;
- physical and model binding of the NDT system to the technological process of production;
- intelligent measuring converter with self-testing functions;
- software with deep learning functions (neural network model);
- transition from NDT to CM of products and technological process of production;
- extended automatic calibration interval.

However, the system does not use cloud technologies, there is no access to control results from third-party organizations, other Internet technologies are not used, which should become key for distributed smart factories. All procedures related to data storage and processing are implemented within the closed internal networks of the concern, ensuring security when using them. Examples of the results of inspection of parts of complex shape are shown in Fig. 7

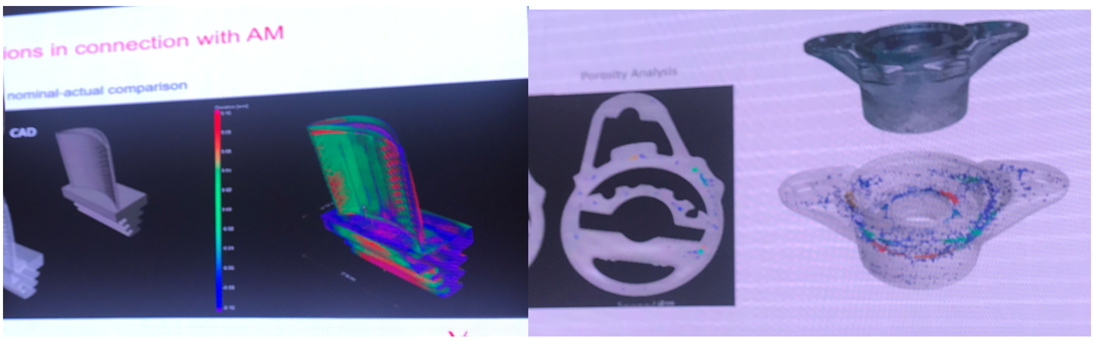


Figure 7. Results of automatic control of parts of complex shape with gradation of discontinuities and allocation of defective areas or sections of products.

Toyota Concern, with the participation of Tessonics, has developed an automatic production line for welding car bodies with a built-in system for monitoring the welding process and controlling welding equipment directly in the welding process. The uniqueness of the equipment is that a cooled ultrasonic combined piezoelectric converter operating in echo mode is built into one of the welding electrodes (Fig. 8).

During the welding process, the formation of the welding core is controlled. The graphical (restored) image allows you to evaluate the parameters of the forming core during welding and adjust the parameters of the technological process. At the same time, the depth of penetration of the welding core into the plates, the moment of the beginning of melting, the rate of solidification of the melt, the fact of splash and the moment of splash are monitored in real time with the possibility of operational control of the parameters of the welding process in real time. Modeling of the control process involves the need to take into account the state of the metal during welding, which imposes additional requirements for the validation of the system and the entire complex of hardware and software. Additionally, deep learning systems are implemented (development of appropriate techniques, samples and algorithms). All processes, taking into account their transience, are performed automatically, and self-testing of equipment is also performed automatically, ensuring high reliability of results over long time intervals of operation. The equipment makes it possible to implement another of the requirements – the immutability of the time of the main technological processes when introducing non-destructive testing operations. However, this system also has limitations associated with unresolved issues of security and speed of information transfer using cloud technologies. All information processing and storage processes are carried out using exclusively factory equipment.

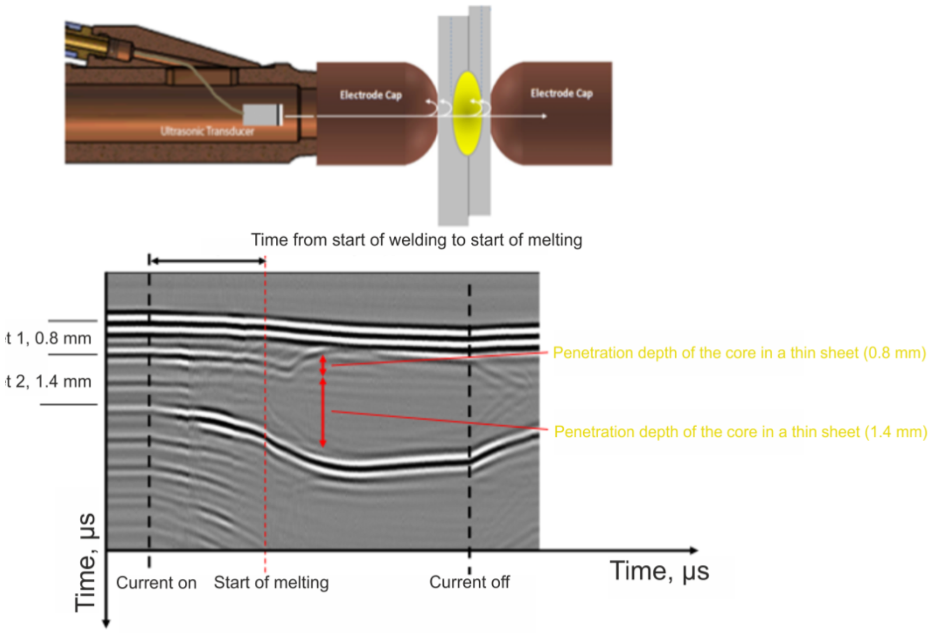


Figure 8. Electrodes of a welding machine with a built-in ultrasonic combined transducer and a time diagram illustrating the process of core formation.

In some cases, the task of automatic non-destructive testing arises during the installation/manufacture of high-tech equipment at various pre-prepared sites, in particular, equipment at nuclear power plants. At the same time, the task is to replace X-ray control with ultrasound. According to the requirements of ROSATOM concern, ECHO+ developed an autonomous system of dimensional ultrasonic automatic testing of welds using TOFD methods and phased arrays (Fig. 9). The tasks were solved:

- joint coherent processing of thousands of echo signals to obtain images of reflectors with high frontal resolution and low noise;
- reconstruction of the image of reflectors taking into account the effects of refraction and reflection from the boundaries of the objects of control and the change of the type of ultrasonic waves, anisotropic and inhomogeneous properties of the material in the area of the weld and inhomogeneous boundaries of the object of control.

This required the creation of a virtual library of defect images located in the cloud space, as well as methods for their use in reverse transformations and automatic generation of control results.

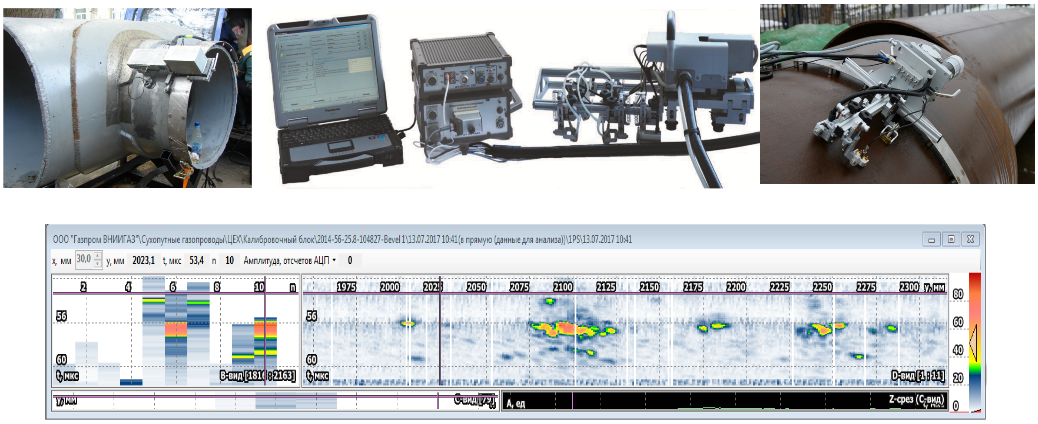
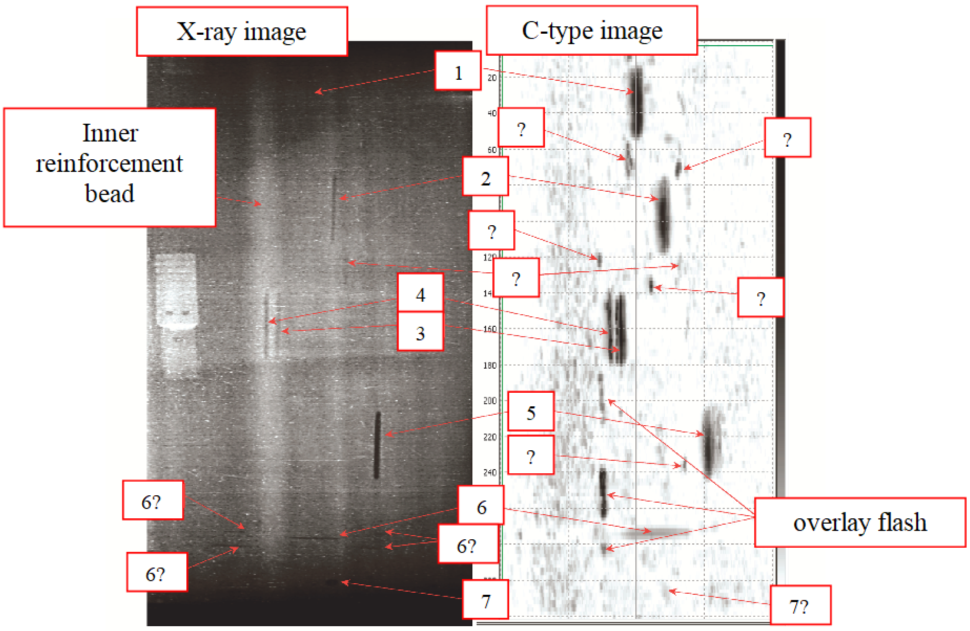


Figure. 9. Autonomous system of dimensional ultrasonic automatic flaw detection during weld inspection using TOFD and phased array methods and automatic generation of control results

The use of the methods, technologies and techniques of reverse transformations indicated in Table 1 in combination with cloud technologies allowed us to achieve ultrasound control results comparable to X-ray (Fig. 10).



a) b)

Figure 10. X-ray of the entire sample *(a)* and the C-type image collapsed to the maximum, obtained as an average combination on a transverse wave in triple scanning mode *(b)*

However, the main issue limiting the use of the control system is the need to use cloud technologies, secure storage and access to virtual models and images of typical internal defects, as well as the uncertainty of verification and validation procedures for models and methods of non-destructive testing.

Achievements in the application of contactless methods and technologies for non-destructive testing and monitoring should also be noted. When considering the tasks that are key in the directions of INDUSTRY 4.0 and NDE 4.0, attention is also focused on the need to condition monitor of products throughout the entire life cycle and the need to develop non-contact methods and technologies for non-destructive testing. As an example of solving such problems, we can cite the joint work of Boeing, Airbus and Automation Technology (FRG) – technology and methodology for condition monitoring of a new generation of Boeing 787 and Airbus 350 aircraft with a large number of fiberglass elements and assemblies in operation. One of the main tasks is one hundred percent high–performance NDT of the fuselage skin during routine inspections in hangars and operational NDT in the field in case of mechanical impacts on aircraft structural elements (bird strikes, lightning strikes, collisions with ground equipment, etc.). The Commercial Aviation Composite Repair Committee (CACRC) faces these challenges when it is necessary to make operational decisions on defects and repairs on different continents. It is the active thermography that meets the specified requirements for these aircraft models. The form of accounting documents allows you to send them to highly qualified experts anywhere in the world (for example, to design bureaus) to make a decision about the level of risk of defects and the need for repairs. Methods of active thermography and equipment manufactured on their basis are increasingly being developed as the basis for newly designed large-sized aircraft and rocket products. In particular, work is underway on the use of eddy currents as a source of thermal loading, issues of automated control with the use of multi-coordinate robots, etc. are being solved. The described system includes one of the variants of the C-CheckIR portable mobile active thermography complex (Fig. 11), methods of application, software for non-base binding of control results to digital counterparts of aircraft, automatic interfaces for transmitting protected information, systems for automatic processing of results and deciding on the criticality of identified structural damage and issuing conclusions on the need for repair work and stopping operation (Fig. 12).

The system provides almost complete automation of the transmission and processing of information, as well as partial automation in the formation of a list of recommendations for operating organizations. During the development, the issue of information protection during its transfer from the place of control to the head offices of aircraft development firms was resolved. It can be argued that this system provides a risk-oriented approach to the operation of high-tech equipment in a distributed system of operation and maintenance.

There are still quite vivid examples of solutions in the field of non-destructive testing and condition monitoring, which can generally be attributed to the direction of NDE 4.0, including in the field of additive technologies. However, it should be noted that they are local in nature and are considered by many experts as achievements in the field of robotics and automation of measurement information processing processes, and not the sprouts of truly revolutionary changes.

Figure. 11. C-Check IR active thermography system. Variants of execution and application.

a) *b)*

Figure 12. Linking of flaw diagrams of sections in the area of the portholes and the wing with the image of the aircraft in the report document for subsequent processing of the results in relation to the digital twin of the aircraft and decision-making *(a)* and the flaw diagram of the places of stratification of fiberglass elements of the fuselage (*b*)

Conclusion. Integration of INDUSTRY 4.0 and NDE 4.0. Some interim results

The past ten years allow us to summarize some results and link the results of the INDUSTRIE 4.0 project (INDUSTRY 4.0 directions) and the interdisciplinary direction NDE 4.0, actually initiated by specialists in the field of NDT.

First of all, it should be noted that in parallel with developments in the technical field, within the framework of the strategic initiative INDUSTRIE 4.0, various problems and risks associated with the implementation of the project were identified: information security, changes in the labor market (training in new competencies, the disappearance of old professions), involvement in the process not only of industrial giants and state corporations, but also and the inevitable involvement of small and medium-sized enterprises, which form the basis of the German and world economy. It seemed that something grandiose was about to happen. Industry 4.0 will finally move from the planning and research stage to the workshops and begin to bear fruit. Ten years have passed, new technologies are really impressive. But, in most cases, they were created, in fact, outside the framework of the German project and do not relate to the reform of production as such. At the same time, it is argued that the real revolution is still ahead. Industry 4.0 has not yet reached the goal, the first decade was an academic one. But will the market give companies another ten years to build up?

Surveys of German enterprises revealed the problems of Industry 4.0 stalling, including: insufficient financial resources (77% of respondents); confidentiality requirements (61%) and IT security (57%); lack of specialists (55%). Despite the fact that 95% of German industrial companies still consider INDUSTRY 4.0 as a chance for their business, two-thirds (66%) honestly admitted to lagging behind [5]. In recent years, the increase in labor productivity in Germany is the lowest since the Second World War. There is no surge associated with INDUSTRY 4.0, with the exception of a small number of local solutions within the world's leading concerns, for example, Siemens. Many manufacturing companies have switched to implementing a variety of digital systems, but there is no clear return on these investments yet. At the same time, the fundamental problems left "unattended" in the workshops remain unresolved. It is obvious that it is necessary to take a sober look at the inevitability of the introduction of digital technologies as the basis of the entire fourth industrial revolution (and after all, only ten years have passed), and again (in forty years!) to confirm the correctness and inevitability of the manifestation of the Solow paradox (productivity paradox) [6], defined in the eighties of the last century as a perceived discrepancy between the indicators of investment in information technology (key in the INDUSTRIE 4.0 initiative) and the indicators of output at the national, and currently international, level. This once again confirms the conclusion that once again we are seeing a delayed economic effect, which has been repeatedly observed with the introduction of truly breakthrough technologies. In particular, in the electric power industry, where the effect became clearly noticeable only 40 years after the start of electrification. A similar pattern has been observed during the years of the INDUSTRIE 4.0 project. German enterprises have been investing more and more in research and development (R&D) and information technology in recent years. But the problem is that investments in improving products, processes and equipment are being reduced at the same time. There is a decrease in the rate of productivity growth. Also, as the reasons for the paradox, it is necessary to single out managerial mistakes associated with an objective lack of competence and experience in global digitalization, the resulting insufficient use of the potential of new technologies, the negative consequences of increasing the volume of information, high costs for improving technological processes during the introduction of information technologies, inflated expectations. It must be recognized that it is not necessary to expect ultrafast economic results from digital transformation and the introduction of new technologies.

At the same time, the following thesis should be the key: digitalization of inefficient processes leads only to inefficient digital processes, that is, only an integrated approach will allow achieving significant results.

There are still quite vivid examples of solutions in the field of non-destructive testing and condition monitoring, which can generally be attributed to the direction of NDE 4.0, including in the field of additive technologies. However, it should be noted that they are local in nature and are considered by many experts as achievements in the field of robotics and automation of measurement information processing processes, and not the sprouts of truly revolutionary changes.

The key tasks and forecasts, divided into three time intervals, given in Table 1, as well as the specified basic general technical tasks, with their complex solution, could in the past ten years and may in the future provide technical and economic benefits within the framework of the NDE 4.0 direction. Some methodological and technical issues/tasks in the field of NDT methods, tools and technologies (generalized first five-year forecast), which do not require joint efforts on a national scale or at the interstate level, are successfully solved by firms at the expense of their own material and intellectual resources or with little government support. However, the tasks within the framework of a ten-year generalized forecast, as well as the identified key general technical tasks, not to mention the tasks of a twenty-five-year forecast, cannot be solved within the framework of firms and even concerns, since they are interdisciplinary in nature and, in general, require some kind of coordination and approval of approaches at the legislative level (standards, regulatory documents, approved methods, etc.).

Indeed, the analysis shows that, in general, the main tasks of the generalized first five-year forecast over the past ten years have been fulfilled. Therefore, when summing up some results of the development of the NDE 4.0 direction, taking into account the volume and complexity of the tasks of the next two stages and the already mentioned general technical tasks, it should be stated as follows:

- the direction is interdisciplinary, covering the widest areas of knowledge and technology, ranging from the fundamentals of physical methods for obtaining measurement information, microelectronics and programming, metrological support, to the safe transmission, storage and processing of measurement information while ensuring free access to it by specialists in the field of technical diagnostics and other related fields of activity;
- it is necessary, first of all, to resolve issues in the field of terms and definitions, reasonably linking them, but by no means copying them, with terms and definitions already approved in a number of national standards in terms of the INDUSTRIE 4.0/INDUSTRY 4.0 strategic initiative;
- it is necessary to organize the NDE 4.0 platform under the auspices of one of the national societies, either EFNDT or ICNDT (by analogy with the organizational decisions taken within the framework of the INDTRIE 4.0 strategic initiative). As a last resort, try to open the NDE 4.0 section on general industrial platforms, for example [2];
- the direction can really develop only within the framework of the strategic initiative INDUSTRIE 4.0/INDUSTRY 4.0 in close cooperation with specialists in related fields of activity, primarily materials scientists, technologists, specialists in the

field of mathematical modeling, information processing and transmission, as well as standardization;

- the direction requires the joint efforts of specialists not only at the national level, but also at the international level;
- specialists in the field of NDT and CM should participate in the work of professional groups that solve issues of digitalization in the production and management spheres;
- special attention should be paid to interaction with the metrological community, as there has been a rapid transition from non-destructive testing as tests to measuring non-destructive testing using digital models in the framework of automatic production and measuring systems operating in a continuous cycle, involving self-testing and auto-calibration. Interaction is possible on European or national metrological platforms.

Taking into account these requirements, which in fact amounts to combining the efforts of communities of specialists and scientists of different profiles at the international level, allows us to hope that in the next ten years – for fifteen years, the tasks of a ten-year generalized forecast will be solved and the foundations will be laid for automatic multiparameter non-destructive testing and condition monitoring of high-tech products, complex technical systems and technological processes of their manufacture, as well as a risk-oriented approach during operation until disposal, ensuring the safety and comfort of life for all mankind.

On the positive side, I would like to note that an active group "NDE 4.0" has been formed in ICNDT, which includes leading specialists from national societies in Asia, Europe and America. The main directions of work were formulated and priorities were identified, ways of interaction with ISO were outlined, issues of coordination of the work of associations of specialists and national societies are being resolved, topical issues are regularly discussed at world, European and regional conferences on non-destructive testing.

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