Development of measurement science in the context of the fourth industrial revolution

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Abstract. The fourth industrial revolution is characterised by the wide introduction of cyber-physical systems, robotics and the Internet of Things. The efficiency of smart cities, smart manufacturing, smart transport, etc. can be provided only if the measurement information coming from sensors is trustworthy. In each facility, the number of sensors can vary from thousands to tens of thousands. The avalanche-like growth in the number of measuring instruments should be accompanied by quite frequent check of their metrological serviceability. In this case, a significant reduction in maintenance labour costs can be achieved by increasing calibration or verification intervals by many times. The development in this direction is challenging because of the growing demand for the increase in the number of complex properties that should be quantitatively estimated. The fundamentals of metrological check and features of applying object digital twins for debugging multichannel measuring systems have been given. The need for international standards in this field has been emphasised.

1. Introduction

Many publications emphasise that the fourth industrial revolution is coming: robotics conquers the world, cyber-physical systems control plants and transport, while the Internet of Things incorporates into daily life.

Metrology experts can put the question whether this revolution influences the development of measurement science, in particular, in the field of non-destructive testing and condition monitoring, and if so, how it manifests itself.

Before answering this question, it is worth noting that the systems mentioned above as well as facilities typical for the oncoming era (smart cities, smart manufacturing, smart transport, etc.) are based on sensors the number of which in one facility can be estimated in hundreds, thousands to even tens of thousands. They include sensors measuring both electrical and non-electrical quantities and operating, as a rule, under harsh conditions with the limited access for maintenance.

Such systems and facilities can be efficient only if the information coming from sensors is trustworthy, while the costs for providing the required trustworthiness do not exceed a permissible limit.

Hereinafter, trustworthy information implies that information comes from a sensor or measuring instrument including it, which metrological characteristics and application conditions correspond to the rates specified in documentation.
According to Murphy’s laws, “anything that can go wrong will go wrong. If anything simply cannot go wrong, it will anyway.” Until now, the most widely-spread method to provide measurement information trustworthiness is calibration or verification. As a rule, these procedures are carried out dismantling the devices from the equipment where they are embedded. Ideally, checking should be carried out periodically whether in the course of measuring instrument operation, measurement conditions correspond to those specified in technical documentation.

At the beginning of the 21st century, at least in Russia, a typical calibration or verification interval is one or two years. However, even for such an interval, occurrence of metrological faults that can cause spoilage in production including cases at the prototypes of smart manufacturing (automatic shop floors). As applied to measuring instruments built in the equipment of power plants or transport, metrological faults can lead even to catastrophes with human loss. The tragedies with passenger planes Boeing 737 Max 8 in Ethiopia and Indonesia can be considered as an example.

Correspondingly, the growth in the number of sensors and other measuring instruments should be accompanied by applying a frequent automatic check of their “metrological health” (at least, with regard to the main characteristics) in the course of the calibration or verification interval. As a result, a significant reduction in maintenance labour costs can be achieved increasing calibration or verification intervals by many times.

However, it is not only the dramatic growth in the measuring instrument and channel number, which distinguishes the fourth industrial revolution. (This fact itself causes serious concerns that the efficient operation of the above-mentioned facilities and systems in case of using traditional operations of metrological maintenance and intervals between them, is possible.) For it, integration of objects located far from each other by multichannel measuring systems (MMSs), is characteristic.

These aspects of building MMSs result in new problems:

a) providing noise immunity and security of transmitting measurement information over long distances;
b) transmission of information basing on standard protocols;
c) using wireless interfaces to connect measuring instruments with information networks;
d) automatic determination of transmitting information priority from measuring channels, e.g., depending on changes of output information and its importance;
e) application of cloud technologies in intermediate means for transmitting information;
f) variation of measurands and the number of measuring channels during operation;
g) real time data processing.

All these features give grounds to draw a conclusion that a necessary condition for realising the fourth industrial revolution is the development of measurement science in the new fields, primarily, in the field of timely providing customers by trustworthy information from sensors, other measuring instruments, and MMSs. The most significant and actual direction is the development of methods that enable organising automatic check of measurement information trustworthiness including methods of both checking an uncertainty variation and its correction if necessary.

2. Widening the spectrum of properties that should be quantitatively estimated

The development of the methods for providing customers by automatic checking trustworthiness of measurement information is complicated by the growing demand for the increase in the number of properties that should be quantitatively estimated. Material and other product properties as well as their variation in the course of operation, are among them. For example, they include those determining the state of building structures, technical systems, etc. Hereinafter, these properties are called complex. Until recently, mainly, they have been estimated qualitatively.

The oncoming era features a sharp growth in the communication of specialists from various countries as well as in material, product and technology trade. Therefore, quantitative evaluations of complex properties are particularly required, metrological comparability, compatibility, and traceability being necessary for them.
The simplest method to solve this problem is to apply a reference material that is a “bearer” of the property being measured. Such a solution is efficient in local situations. However, in most cases, it is accompanied by a number of problems concerning the evaluation of uncertainty as well as proof of metrological comparability, compatibility, and traceability of the quantitative evaluation results. The problems are exacerbated if the results are obtained in experiments that were carried out in various time with measuring channels placed in different locations.

Another way is getting expert (panel or jury) evaluations based on the ordinal value scale, expert objectivity being evaluated according to a special scale. This method has similar drawbacks.

To meet the considered requirement efficiently, complex properties should be defined as multidimensional (multiparametric) ones. Such a definition requires that relations between a multidimensional quantity and set of quantities forming it are revealed. This statement is adequate to designing a measurement model. According to the International Vocabulary of Metrology [1], measurement model is a “mathematical relation among all quantities known to be involved in a measurement”.

This definition is of a general nature. To develop a special model, it is necessary to determine a lifecycle stage of an object that is the “bearer” of the complex quantity, which will be the output quantity (measurand) in the measurement model. In particular, it can be the stage of manufacturing or operation.

Then, it is expedient to limit the set of parameters to those that can impact the output quantity significantly at the corresponding stage taking into account a permissible uncertainty.

An important feature of multidimensional quantities that characterises product properties is a degradation tendency that manifests itself in the dependence of such quantities on time. At the manufacturing stage, this feature forms severe rates of the technology operation duration, which is necessary to take into consideration while developing procedures of quantitative evaluations of the product properties.

The same feature also entails the need for supplementing the evaluation of multidimensional quantity, e.g., strength, by the estimation of an interval, during which an object including this product, e.g., a bridge or turbine unit, will not require repairing due to the defect of the considered product.

However, it is not enough to base only on a calculation evaluation of this interval and previous experience. Because of variations in operation conditions or deviations from manufacturing technology, the calculation evaluation can become non-trustworthy, which can lead to catastrophic consequences.

Therefore, the monitoring of the quantities determining the state of a specific object in the course of its operation is being applied more widely. Of course, in addition, one should not disregard a traditional method of non-destructive testing, namely expert testing method.

The development of measurement model opens up new prospects.

A digital twin based on the model can be developed. It will reproduce a measurement object in the entire range of its parameters and influence factors. The use of the digital twin makes it possible to debug a monitoring algorithm and software and then realise a corresponding measurement model in a measuring instrument or MMS.

While forming the digital twin of a measurement object it is necessary not only to determine characteristics linking influence quantities with a multidimensional quantity, but the probable speed of influence quantity variation under expected conditions. The conditions can include thermo-technical, mechanical, electromagnetic, and other influence quantities, which leads to certain difficulties.

The analysis of the formation “mechanism” of a multidimensional quantity can facilitate the solution of the problem. As a rule, realisation of such a method requires organising cooperation of metrology experts, who deal with quantitative evaluations of production, with experts in technology.

3. Automation of “metrological health” checking

In the mid-1980s, at the D.I. Mendeleev Institute for Metrology, for the first time in the world, the development of the theory on automatic checking the “metrological health” of measuring instruments
was started. According to the Russian regulatory document [2], it was called a “metrological self-check” (MSC). Later, a number of sensors, measuring instruments and MMSs with MSC have been designed. Some examples are given in [3-5].

An MSC basis is the application of redundancy that can be of time (frequency), space (structural), information (functional), or combined type.

Time redundancy uses supplementary measurement operations carried out more frequently and/or applies wider frequency band than it is necessary for solving the main measuring task.

Space redundancy relies on supplementary elements (material measures, measuring transducers, or measuring channels).

Informational redundancy means that a supplementary dependency of an output signal on a measurand or between output signals is used.

As applied to a wide spectrum of physical measurands, two types of the MSC exist:

- a direct one that reminds calibration is based on the application of an embedded element, e.g., redundant measuring transducer or material measure of a higher accuracy (at least, in a narrow range, this component should have a higher metrological reliability than the main part of a measuring instrument);
- a diagnostic one that provides the check of the part of uncertainty.

The direct self-check can be especially efficient in instruments designed for electrical quantity measurements and in the near future, in measuring instruments with simplified embedded quantum mechanical standards.

The diagnostic self-check does not require applying the embedded instruments of a higher accuracy and can be organized for measuring practically any quantities including multidimensional ones. It is carried out by the deviation evaluation of a diagnostic parameter that characterises a critical uncertainty component from its reference value fixed in the course of a previous calibration. The critical component is a predominant one or that being characterised by a tendency to grow quickly.

In the course of operation or another stage of life cycle of a “bearer” of a multidimensional quantity, its parameters can change to some extent. To exclude dangerous metrological consequences, the critical uncertainty component applied for the MSC, as a rule, should be about 70 % of the whole uncertainty. In this case, the opportunity appears to replace the whole uncertainty with its critical component in measurement instrument specifications.

However, this decision is not the only one. The MSC enables automatic diagnosing the uncertainty growth, which opens principally new opportunities for specialists in measurement technique design. At the stage of development, the calibration curve of a primary measuring transducer can be optimized to improve its metrological fault tolerance.

Besides, in measuring instruments and multichannel measuring systems with the MSC, hardware and software can be included, which will make it possible to prognose the change of uncertainty with time and if necessary, automatically correct it, which will give grounds to prolong a calibration or verification interval.

To conceptualise prospective directions of measurement technique, to pay attention to the analogy between biological system evolution and technical system development, is useful. The duration of biological evolution is much more than that of technical civilization, which enables searching hints concerning the future in the decisions originated during evolution. One of such hints: intellect has been formed by joining a number of autonomous nerve components, each of them being connected with one or a few biological sensors. The joint structure is provided by a “mechanism” that controls characteristic stability of the components, which Russian academician N. Bekhtereva called “error detector” [6]. The analogy between the MSC in MMS and “error detector” in the nerve system seems to be evident.

Until recently, the MSC has been implemented in industry comparatively slowly. To a significant extent, the delay was due to the fact that customers insufficiently understood the necessity of the supplement cost of MSC organisation. Besides, they were not sure that taking into account the
required increase in a current product cost, the demand for the MSC will increase in comparison with the demand for products without the MSC, which were manufactured by their competitors.

To accelerate the MSC introduction, a number of regulatory documents were developed and issued under the supervision of the present paper authors. The first of them was recommendation [2]. Later, based on the experience gained for 20 years, Russian national standard [7] was prepared where sensors and MMSs provided by the MSC were called intelligent ones. This term was accepted taking into consideration the analogy with the “error detector” [6] as well as survey results [8].

Then in two years, one more national standard [9] was developed and issued. It can be considered as a guidance on the development of intelligent measuring instruments including sensors as well as MMSs.

Actual fields of metrology development while implementing the MSC becomes the development of methods intended for the virtual testing of MMSs. Virtual tests are those that under laboratory conditions, enable testing the reliability of a MMS including metrological reliability. (Metrological reliability of a measuring instrument or MMS is the reliability regarding metrological serviceability.) They are particularly efficient as applied to MMSs with the MSC function, which include channels located far from each other.

The programme of virtual tests is based on the analysys of the time variations of sensor measurement information and corresponding influence quantity values. Such information can be obtained from the results of a rather representative experimental operation of a MMS analog or its version with a fewer number of measuring channels.

A test object is a software and hardware complex, chosen sequence of sensor signal records being led to its input. According to the analysis results, the most dangerous parameter ratios are selected and an object digital twin is developed. It enables debugging algorithms and software of the MMS with MSC, providing efficient monitoring and forming an alarm signal for transmitting to a control centre if parameter values approach unacceptable limits.

In the end, to check whether computing capacity and operation speed are sufficient, originating sensor defects can be detected, necessary command are formed, etc., becomes possible.

Such tests enable providing economy at the stage of the system development due to both selecting the combination of factors that can impact significantly on measurement results and determining the most efficient protection measures, including those related to the requirements for sensors.

The MSC concept and examples of its realization were discussed at many international conferences and reflected in published papers, books, patents, and regulatory documents. In Great Britain, China, USA, Germany, and other countries, the works on the MSC are also carried out, but in a number of cases, they have another name, e.g., self-validation. The direction considered is actual for various measurements, including non-destructive testing.

In recent years, practical interest in the MSC in Russia is growing. With the participation of the present paper authors, an intelligent MMS has been designed that monitor the state of fastening assemblies of the turbine unit cover at a hydroelectric power plant. It is based on automatic tracking the ratio of different cover point displacements regarding a housing. As a result of the MSC, sensors that are faulty (with the diagnostics of a defect originated) as well as the appeared slope of the cover, can be revealed. If dangerous situation arises, a corresponding signal is transmitted to a control system.

A number of measuring instruments and MMSs with the MSC have been developed that enable justifying the multiple increase in calibration /verification interval in comparison with analogs, e.g., flowmeters taking into account non-uniformity of mixtures in pipelines [10], systems designed for measuring the force of straining slings that increase the strength of nuclear reactor vessels [11], etc.

To ensure the efficiency of the considered method, international standards in the corresponding field are necessary. This judgement does not contradict a new national legislation tendency related to measurements, which has arisen in economically developed countries. According to it, the responsibility for non-trustworthy measurement results should be delegated to the customer of measuring instruments and MMSs. Of course, the state should provide customers not only with the
possibility to calibrate corresponding instruments in a state or private organisation, but opportunity to choose which measuring instruments or MMSs they should purchase to improve the economic efficiency of their activities. International and national standards in the sphere of measurement result trustworthiness should help engineers with solving this task.

For example, terms “intelligent” and “smart” are widely used in the descriptions of measuring instruments and MMSs. However, in most of them, these terms only indicate that some data processing is fulfilled in these devices. In some cases, an MSC function can cover, e.g., 10% of the uncertainty, in others, this share is significantly greater, but mainly, such a function is not included. The arbitrary practice while preparing technical documentation should be excluded by an international standard.

Information on the metrological trustworthiness of measuring instruments (including sensors) and MMSs as well as availability of the MSC function and uncertainty components that can be checked, should be included in technical documentation.

This information will enable turning to the insurance of objects that can undergo danger in case of decreasing measurement information trustworthiness. Such a step can lead to the growth in the safety of technical facility and system functioning and thereby, will contribute to the acceleration of industrial revolution development.

The increase in the labor costs of metrology specialists to provide the information trustworthiness and measurements of multidimensional quantities, will be compensated, to a significant extent, by decreasing the volume of metrological maintenance works at the operation stage.

If the measuring instruments and systems with the MSC function and simplified quantum-mechanical reference standards embedded in equipment will be applied widely, for the most means, periodic calibration or verification will not be necessary. To replace them in 10-15 years as obsolete ones, will be reasonable.

4. Conclusions

The analysis of the features and tendencies specified for measurement science development including those in the field of non-destructive testing, enable coming to the judgement that mainly, measurement science has completed the stage of specialisation on physical measurement areas.

However, in the era of the fourth industrial revolution, measurement science is expecting a new growth. The accent will be placed on achieving the trustworthiness of multidimensional quantity measurements and monitoring including the use of non-destructive testing methods. The spectrum of multidimensional quantities will cover natural and technical objects, systems of such objects as well as the processes of their development and interaction.

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