Actual measuring technologies of Industry 4.0 and analysis of their realization experience

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Abstract. Civilization development requires a multifold increase in the volume of measuring information. Such an increase, to a significant extent, is caused by the necessity to solve qualitatively new measuring tasks. To meet this need is possible by the transition to new measuring technologies. The experience of the D.I. Mendeleyev Institute for Metrology in developing actual technologies, in particular, metrological self-check and virtual tests, proves their efficiency and discloses realization features.

1. Introduction

For this century, the requirement is characteristic to provide a fast growth in the number of sensors as well as other measuring instruments (MIs) and measuring systems (MSs), their computerization and the increase in the MS channel number. Such a need is caused by the origination of cyber-physical systems, spread of “smart” transport, “smart” healthcare, “smart” home, “smart” cities, “smart” energetics, and “smart” manufacturing.

Another actual requirement of modern society is the increase in the variety of multidimensional quantities that should be measured.

This requirement is caused by globalization and raising the living standards of society, as well as the need to evaluate the quality of products, services, and human properties including the state of health, professional skills, capacities for certain abilities, etc. These evaluations, at least, should be characterized by metrological comparability and compatibility of results. Development of the models for measuring multidimensional quantities accompanied by the assessment of a significance coefficient of each input quantity in the measurement model, is of a particular demand with respect to the measurements of time-varying quantities, e.g., quantities related to the state of human health or forecast of disease development.

The society requirements bring forth attempts to meet them, which leads to the increase in the number of corresponding publications. As it is noticed in [1], tendencies in measurement science development reflected in these publications, play a forerunner role in the Industry 4.0 era.

Interdisciplinary projects become an important part of metrologists’ activities [1]. It is not by chance that IMEKO TCs organize joint Symposia more and more often.

We observe a snowballing growth in the volume of measuring information required by society. However, the increase in the metrological reliability of MIs is significantly slower. This fact exacerbates
the issue of providing the trustworthiness of information both at the stage of its receiving and transmitting through communication channels to automatic control systems.

Hereinafter, measuring information is called trustworthy if it is obtained from MIs that are “healthy” in the metrological sense and operate under environment conditions permissible for them.

A conventional system of metrological maintenance, which is based on periodic calibration of MIs at one- or two- year interval, cannot meet the increased requirements of society in trustworthy measuring information, in terms of economic and safety reasons. No wonder that the issues of measurement trustworthiness of cyber-physical systems, their reliability, resilience (survivability) as well as lifecycle including maintainability, are included in [2].

Among actual trends of measurement science development, the following tendencies should be mentioned (references below are of an illustrative but not exhaustive character):

- processing big data volumes and visualizing high-dimensional information [3];
- providing access, storage and transmission of measuring information, which is protected from noise as well as unintended and unauthorized access, change, damage, destruction, or use [2], including cases of measuring systems with hundreds and thousands of channels that are separated in space by long distances [4];
- organizing an automatic validation of MSs, automatic correction of measurement uncertainty and even calibration [1];
- testing MIs and evaluating measurement uncertainty by using simulation and virtual processes [3, 5].

To develop new measuring technologies is necessary, which will enable producing MIs with automatic functions, which provide required trustworthiness and accuracy, labour costs reducing in the course of MI operation.

Realization of two requirements of society mentioned above, can be efficient only in case of developing international regulations on the new measurement technologies and requirements for measurement models as well as for MIs and MSs based on these technologies. The standardization in this field should rely not only upon scientific hypotheses, but also upon the experience of engineering.

Measuring technologies enabling fulfilment of these requirements have been developed at the D.I. Mendeleev Institute for Metrology (VNIIM), which is a leading scientific centre of the Russian Federation in the field of metrology. These technologies were developed along with specialists from other organizations. The experience has shown that these new technologies offer opportunities for solving other actual tasks. This can serve as an indicator that in the 21st century, the investigations in the measurement science open up wide horizons.

Some measurement technologies aimed at automation of providing measurement trustworthiness, are considered below.

2. Automatic checking the trustworthiness of measurement results

2.1. Metrological self-check

Metrological self-check (MSC) is an automatic check of the metrological “health” of a MI or MS in the course of its operation carried out using an accepted reference value generated with the help of an additional (redundant) embedded instrument (a measuring transducer or material measure) or an additional parameter of an output signal [6]. The term “accepted reference value” corresponds to the same term given in [7] and the term “reference value” according to [8]. If the MSC is accompanied by evaluations of uncertainty or error, it can be called “self-validation”.

The organization of the MSC is aimed at monitoring changes of metrological characteristic from their values fixed in the course of previous calibration. The MSC provides application of supplement data as reference values. For obtaining information on a measurand, these supplement data are not necessary, and, accordingly, are redundant.

The technology that enables checking the state of metrological “health” of MIs in the course of their operation, was proposed in [9] and later justified theoretically and experimentally in [10-12] and other
papers. In regulations, for the first time, it was reflected in Russian document [13], later, partly, in [14, 15] and in more expanded form in [6, 16]. Unfortunately, this complex of publications is not sufficiently known to specialists who deal with Industry 4.0 issues. For example, in [1] published in 2016, its authors write that such a field neither has yet been considered in measurement theory nor taken up in practice.

Two main types of the MSC can be used: a direct MSC or diagnostic one. The former provides that in a MI or MS, a material measure or measuring transducer that is characterized by a higher accuracy, is embedded. As a rule, their measurement range is smaller or response time is greater. The direct MSC reminds calibration. An embedded cell (capsule) containing some metal with a known value of the melting (hardening) temperature, i.e., the metal fixed point, can be a simple example [17, 18]. When the temperature of the environment changes, the metal is melting or hardening and a “plateau” in a diagram “temperature – time” is forming. When the temperature corresponds to the metal fixed point, the deviation of the measured temperature from the reference value, enables estimating the uncertainty.

However, to reduce significantly labour costs related to metrological maintenance due to the noticeable extension of a calibration interval is possible only if the metrological reliability of the embedded material measure or measuring transducer is much higher than that of the MI or multichannel MS. The direct MSC can be efficiently applied for measurements of electric quantities, but for non-electric ones it can be used only in rare situations.

The diagnostic MSC provides automatic monitoring and, if necessary, correcting the uncertainty, but these operations do not concern the uncertainty as a whole. They relate to its component that is critical, i.e., predominant or inclined to fast growth. (In some cases, it can be a group of components.)

This circumstance requires that at the stage of developing a MI or MS with the MSC of such a type, theoretical and experimental investigations should be carried out, which are aimed at determining the critical uncertainty component as well as factors significantly influencing the uncertainty. The efficiency of the development as a whole, depends on the difference between the chosen uncertainty component and others. After that, the task to reveal or artificially introduce space, time and/or informational redundancy in the MI or MS should be posed. In many instances, the decisions of such tasks can be of an inventive character. The redundancy should enable measuring some supplementary quantity, the value of which strictly depends on the critical uncertainty component, but weakly depends on the factors influencing the critical component. This value can be accepted as the reference value.

This additional quantity allows evaluating the time variation of the critical uncertainty component through the deviation of the above-mentioned quantity from its reference value determined at the stage of calibration. If the critical uncertainty component increases up to a dangerous level, it can be automatically corrected. Meanwhile, corresponding information comes to an automatic control system.

This measuring technology makes it possible to extend the calibration interval several times. The efficiency of such a technology was confirmed in experiments when developing MIs and MSs designed for measuring displacement, pressure, level and specific electrical conductivity of liquids, flow rate, etc. A number of regulations, including state standards [6, 16], support the technology. According to the terminology [6], sensors and MSs provided by the MSC function are called intelligent ones.

Spaceships and nuclear reactors more than other technical facilities require trustworthy information coming from embedded MIs and MSs, since for many years, they are practically not available for traditional metrological maintenance.

This circumstance became an incentive for VNIIM to develop an intelligent MI that determines the position of a control rod in the nuclear reactor of the VVER-1000 type. Within the range of 4 m, it applies a code scale. Sensors of such MIs are located inside the primary circuit of the reactor, their housing being mounted at a reactor cover. They operate at temperatures up to 325 °C, under high pressure and a strong radiation flux.

In the tube sensor housing with the length about 6 m, a set of inductance coils, i.e., sensing elements, is fixed. The sensor is located inside a moving tube rack of approximately the same length. A set of bushings made of magnetic and nonmagnetic steel is located inside the cavity of the drive rack rigidly connected with the control rod.
In the developed intelligent MI, any single sensor fault (e.g., any signal wire breaks or any coil fails) does not lead to noticeable metrological failure.

The result is achieved due to additional inductance coils that provide the redundancy of the MI code scale, application of a Ni-Cr wire in them as well as several special supply modes [11 and others].

Experimental investigations of such MIs were carried out at a nuclear plant during a multi-year period. They have shown that the lifetime of these sensors can be extended up to 60 years without metrological maintenance, the trustworthiness of measurement results being confirmed automatically in the course of operation.

However, such a lifetime is necessary for comparatively limited number of applications. In the Industry 4.0 era, for most MIs and MSs, to extend the lifetime without metrological maintenance up to 10-12 years is sufficient. This time interval corresponds to their period of obsolescence.

2.2. Removing the influence of part of critical uncertainty component

For a number of MIs, a factor that significantly influences measurement results, is a quantity changing with time, which characterizes the environment or a measurement object. Sometimes, the value of such a change is unpredictable. In similar cases, to measure the value of dangerous influencing quantity and make corrections is not always expedient.

For example, the humidity of the environment is a dangerous factor for a capacitance sensor that provides measuring the gap between a housing and shaft rotating inside it. The humidity determines a significant proportion of the critical uncertainty component. To provide the invariance of measurement results [19] regarding humidity values, is more efficient. Typically, for achieving such a technical result, the redundancy is also necessary.

In particular, the influence of possible humidity changes on the results of measuring the gap, is removed in the VNIIM capacitance sensor. To achieve this effect, in the sensor two measuring transducers are designed, electrodes being fixed in the housing. Each of them measures the gap through the capacitance between the electrode and the shaft. One of the electrodes is round, while the second electrode is performed in the form of a ring. It has the same area and surrounds the first electrode, being displaced along the direction of a shaft radius by a known distance.

The ratio of signal values obtained from displaced electrodes enables achieving the required effect.

The approach based on the redundancy can be applied for inductance sensors measuring the gap to the rotating shaft that is being magnetized, sensors measuring specific electrical conductivity of liquid, as well as in a number of the other cases.

2.3. Self-check in multi-channel measuring systems

The most efficient way for organizing MSC in multi-channel MSs consists in revealing interconnections between the signals obtained in different measuring channels that are metrologically “healthy”. A characteristic example is an intelligent MS intended for monitoring the state of fastening assemblies of the turbine unit cover at a hydroelectric power plant that has been developed at VNIIM. 80 bolts are located at equidistant points along the cover circumference. Displacement sensors being installed at each eighth bolt measure the displacement (elongation) of the bolts relative to a turbine housing. In this MS, the MSC relies upon the property of such covers to be stiff. As a result, when the cover moves up, down, or at an angle, the values of the signals from metrologically “healthy” measuring channels should correlate with each other since the signals reflect the displacement of the same plane. The uncertainty of the displacement measurement is less than 5 \( \mu m \), while measurement range is \( \pm 3 \ mm \). In the course of the turbine unite operation, according to the MS operation algorithm, the sensors are periodically queried and measurement results come to a data processing unit. The query frequency is constant (about 2 Hz). The algorithm includes preliminary and basic processing.

The preliminary processing enables fulfilling procedures aimed at increasing the efficiency of hardware application and initial statistic data processing. The former task is solved by “thinning” the original data set to decrease the frequency of their further processing. A data smoothing of “thinned” data in non-crossing time windows by calculation of medians, plays the role of the initial statistic
processing. The median is applied since it allows removing outliers and provides the higher accuracy of calculations taking into account available hardware resources. The values of the “tinning” data frequency and time window durability were chosen by simulating the procedures based on signal records obtained from analogues turbine units. Results of simulation also showed that smoothing in a sliding window is not expedient.

Further, smoothing data (the median values obtained in each window) are subjected to the basic processing that includes the procedures revealing current sensor defects (e.g., sticking of a moving sensor part, its detachment, and so on) as well as those determining a slow drift of the measurement uncertainty with its possible correction. To develop each of these procedures, to analyse the signal records obtained from analogues turbine units was necessary. This enabled estimating the parameters of the proposed procedures. For example, to reveal the situation related to sticking of the moving part, requires that the standard deviation (or another measure of dispersion) calculated in each smoothing window should be accumulated for a certain number of windows or certain time. The accumulation duration was chosen based on mathematical simulation.

Time cycles of the procedure operation should be divisible by the smoothing window duration. The shortest cycles corresponding to revealing current defects, e.g., outliers and simultaneous two-directional variation of signals of different sensors, require application of only two smoothing windows that are neighbouring. These cycles use information concerning signal differences calculated for each sensor in the neighbouring windows. The longest cycles aimed at detecting slow uncertainty drift, apply all the data obtained in the course of the previous time of the turbine unit operation.

Current results of the MSC are recorded into a data logger, a time interval being devised to smoothing window duration.

These results include information on:
- significant events that were detected by the corresponding procedures,
- alerts and forecasts related to further operation of the MS,
- possible slope of the turbine unit cover,
- uncertainty drift and necessity to make self-correction.

The MSC provides confidence in the trustworthiness of measurement results and allows defect sensors to be detected. It gives grounds to carry out periodic calibrations or verifications of sensors, as a rule, in the course of planned shutdowns of turbine units. So, as a rule, metrological maintenance procedures can be carried out significantly less often than it would be necessary for MSs without MSC.

The efficiency of intelligent multi-channel MS based on the MSC, stimulated VNIIM to develop MSs with similar functions for other applications.

For example, the MSC was also applied in the MS controlling the ecological safety of the aquatic environment which is used in the system designed for supplying citizens with drinking water. It uses crayfish as “biosensors”. Considering this feature, self-checking provides the identification of metrological faults at the technical part of the system, and, separately, anomalous deviations in the work of “biosensors” [20].

2.4. Virtual testing

Mathematical modelling and virtual experiments are applied in various measurement fields, in particular, in coordinate-measuring machines, for evaluating measurement uncertainty, which is reflected in ISO standard [21]. According to [3], in the era of Industry 4.0, to transfer the method used for virtual coordinate measuring machines to all relevant classes of MIs, is expedient.

In our opinion, this approach is especially actual for multi-channel MSs, the test program of which should take into account the influence of both measurand values covered all their permissible measurement range and various influencing factors. This feature can lead to a noticeable increase in the measurement uncertainty and even to erroneous estimates of the situation being analysed. Of course, such a situation is the most typical for sensors of measuring channels that are very far from each other, e.g., in a system measuring pure water flow rate, which is designed for water commercial accounting within a town or several its districts.
However, as practice shows, even in a multi-channel MS embedded in a unit, combinations of impacts on different measuring channels may appear to be unexpected for metrologists. To take into account all potentially possible versions of impact combinations in the test program is inappropriate for many reasons, including the economic ones. That is why to prepare the test program, it is appropriate to use information gained at the operation of previously used MSs.

At the VNIIM, a virtual test procedure was developed (with the participation of the co-author, a GUAP specialist) applied to the intelligent MS designed for monitoring the state of fastening assemblies of the turbine unit cover at hydroelectric power plants.

Virtual test using an identical MS, was performed in a laboratory. Samples from the signal records played the role of the source of test signals coming to the inputs of measuring channels with disconnected sensors. These records were obtained in the course of operation of similar MSs, which were not provided by the MSC, at the hydroelectric power plant for the two preceding years. They included both records related to transient modes of the turbine units and those simulating sensor signals in the course of operation modes causing special concerns of engineers.

The virtual test allowed checking the MS operation, including the MSC function, for variety of signals coming through different channels to the data processing unit.

2.5. Prospects for the automation of monitoring the measurement trustworthiness

Although works related to the improvement of the MSC theory as well as development of intelligent MIs and MSs mainly are still concentrated at the VNIIM, at present, MSC technology is also used by other Russian organizations, in particular, in Omsk, Moscow, Chelyabinsk, etc. Similar work related to particular measurements, is underway in the UK (Oxford University) and in some other countries.

However, not in all the cases, the self-check takes into account the experience gained in other countries and organizations, which creates obstacles to its widespread introducing into series produced MIs and MSs. On the other hand, not always a diagnostic MSC is focused on monitoring the critical uncertainty component. In some MIs and MSs, to reduce the cost of “intelligent” devices manufactured for sale, only a small part of the critical component is monitored. Application of such technical decisions actually leads to unfair competition of manufacturers and to consumer fraud.

At present, an unjustified delay of MSC widespread introduction is one of the most important problems that should be solved in order to accelerate moving to the Industry 4.0 era.

Crashes of Boeing 737 Max 8 aircrafts in Ethiopia and Indonesia testify that this problem is actual. A crash reason was associated with sensor defects in the Maneuvering Characteristics Augmentation System (MCAS). The Boeing corporation has a software providing alarm signals in case of sensor fault (it can be considered as a simplified version of the MSC). However, before the last crash, only special customers’ requests made the company install this software for a particular fee.

After the analysis of the crashes caused the deaths of hundreds of passengers, the decision was made to install the corresponding software mandatory in all the Boeing 737 MAX aircrafts.

In our opinion, the necessity to use a MSC technology should be related to all the automatic control systems that incorporate sensors a fault of which can result in devastating consequences.

In this regard, there is an urgent need for preparation and publication of international standards both describing known methods of organizing the MSC and establishing requirements for the characteristics of automatic checking the reliability of measurement results as well as for justification of their fulfilment.

3. Conclusion

The development of new measurement technologies based on the fast processing of measurement data including the use of various types of redundancy and cloud computing, has become one of the most relevant trends of measurement science in the coming era. These technologies will contribute to the widespread adoption of intelligent MIs and multichannel MSs in almost all the areas of human life.

To accelerate introducing and improving the actual measurement technologies, a number of international standards should be prepared, which should contain the description of the most demanded
technologies and requirements for the metrological characteristics of measuring instruments and systems that are based on them.

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