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METROLOGICAL SELF-CHECK AND EVOLUTION OF METROLOGY

Roald Taymanov, *Ksenia Sapozhnikova*

D. I. Mendeleyev Institute for Metrology, St. Petersburg, Russia, taymanov@vniim.ru

Abstract: Indications of the crisis in the conventional methods of metrological assurance of sensors are analyzed. The analogy between biological and technical evolutions is discussed. It is shown that the near future is mass production of intelligent sensors and systems with metrological self-check, as well as the transition to a new stage in evolution of metrological assurance of sensors.

Keywords: sensor, metrological self-check of sensors, long term calibration interval, evolution of metrology

1. INTRODUCTION

In a history of metrology the definitions of its problems as well as methods of their solution changed more the once. Such changes were driven by industry and society requirements at each stage of development.

As a result the metrology legislative acts and regulations were revised.

Among the most important changes, we can list development of the state systems of units, transition to the metric system, transition to the SI units, development of standards on the basis of quantum-mechanical effect. The number of less important changes is significantly greater.

Since 60's, the national centres of metrology have had to change focus of their activity following the requirements of the industry. Keeping the control, they delegated a part of the work to other institutions. The national centres of metrology came from concentration of verification work to accreditation of calibration laboratories, and later they came to the "metrology for quality" [1].

In the near future, next changes are expected, which will involve the community of specialists directly connected with metrology.

The American historian of science Mr. Thomas S. Kuhn introduced the idea of "a paradigm" and considered the development of science to be a research standard that defines the spectrum of problems being solved during some time interval. In [2] he presented the development of sciences (and individual branches of sciences within the framework of specific sciences) as a series of phases of "scientific revolutions" (paradigm shift).

According to this theory of scientific revolutions, qualitative change of regulations that scientific community is guiding meets with opposition of a part of the community.

This counteraction appears due to the fear to be fired, necessity to improve qualification, possible loss of a status, etc. In order to soften consequences of the "scientific revolution", it is necessary to explain inevitability of such a revolution and to define new tasks that it will solve.

2. INDICATIONS OF THE CRISIS OF THE CONVENTIONAL METHODS

In metrology, one should expect a forthcoming shift in the practice of maintenance of metrological traceability of measuring instruments, especially in regards to sensors.

The number of sophisticated technical objects is growing quickly. Such objects include automatic control systems containing a lot of embedded sensors. Usually, there are about several tens of sensors in a medical apparatus, about 2 thousand sensors in an airplane, and up to 3.5 thousand sensors in a missile, etc.

Indirectly, intensity of this process is confirmed by 10 – 25 % annual growth of income from sensor sales.

The equipment cost is increasing with increase of its complexity. It is necessary to provide the recoupment of equipment. Therefore, the equipment utilization should be enhanced by decreasing required man-hours and stoppage of work, including those related to maintenance. Decrease in the man-hours is provided by computerization of equipment.

Control system receives information about the parameters of technological process from multiple sensors. Based on measured values, the control system generates commands to switch an operation mode and/or to form an alarm signal. Quality of production, operation costs, and probability of accidents depend on the level of confidence in measurement information. It is particularly important in such fields as nuclear power engineering, cosmonautics, aviation, etc. In some products, even a short-term loss of information from embedded sensors during special operation periods is unacceptable.

The key problems of measurement reliability are related to sensors: their components are ageing and parameters are drifting with time. Sudden failures can also happen.

The sensors which control technological equipment condition and parameters of technological process, as a rule, are under strong and sometimes unsteady impact of the variety of factors. Possible consequences of the impacts are for example, depositions, magnetization and so on. All these reasons deteriorate metrological parameters of sensors and can lead to control errors.

In some cases, the effect of the influencing factor can be weakened by a special design of the sensor. For example, the speed of growth of sediments on a sensor outer surface can be decreased by polishing the surface of the sensor.

However, it is not always possible to develop the sensor with metrological characteristics which do not depend on influencing factors during long period of operation. Economic reasons may play a role as well.

At present, traceability of measurements during operation is assured by periodic calibrations or verifications (hereinafter referred to as calibrations). Accordingly, the level of confidence in measurement data depends on the duration of calibration intervals (CI).

As demonstrated in [3], the measuring instrument failures contains 40-100 % of metrological (degradation or monotone) failures. While the quality of manufacturing improves, a share of metrological failures increases. It is inexpedient to apply fundamental assumptions of the classical reliability theory (independence of failure rates and failure rate stability) to measuring instruments. The use of the methods based on these assumptions leads to major errors.

In order to decrease the risk of error, the Russian state certification centres usually limit CI to 2 years.

However, the cost of sensor calibration is 35 – 300 euro and the number of sensors is growing year by year. If such CI duration is kept, a share of calibration costs in the operating costs will go up to an unacceptable level.

In many cases, it is necessary to interfere in a technological process in order to carry out a calibration. Such interferences lead to additional costs.

Document [4] sets that it is “the responsibility of the end-user organization to determine the appropriate calibration interval under the requirements of its own quality system”. In [5] it is said that “the initial decision in determining the CI is based on the following factors:

- the instrument manufacturer’s recommendation,
- expected extent and severity of use,
- the influence of the environment,
- the required uncertainty in measurement,
- adjustment of (or change in) the individual instrument,
- data about the same or similar devices”, etc.

Application of the method of analogies in order to set the initial CI is not always acceptable: production technologies and important features of design for compared sensors can be entirely different.

It is recommended in [5] to adjust the initial CI during operation in order to optimize the balance of risks and costs, due to a number of reasons, for example:

- instruments may be less reliable than expected (e.g., this can happen due to the fact that parameters of the technological process and materials applied for producing the sensors for which a manufacturer determined the CI and those for producing the sensors purchased are different: in a number of cases, small changes in the technological process are not accompanied by the adjustment in the CI);
- conditions under which a manufacturer specified the CI and the operation conditions for the particular sensor are different;
- the drift determined by the recalibration of the instruments may show that longer calibration intervals may be possible without increasing risks;
- it may be sufficient to carry out a limited calibration of certain instruments instead of a full calibration, etc.

However, in some cases, it is impossible to perform calibrations with a rather short CI, in order to obtain the data necessary for adjusting the CI value for the sensor.

Operation conditions of sensors during several CIs can be different to a great extent. In manufacturing equipment, they can change when correcting the technological process, e.g., in case of production modernization. Operation conditions of sensors, which take place in transport equipment, depend on the intensity of the equipment use.

Taking all the above mentioned reasons into account, a customer does not want to pay (or cannot pay) for special testing in order to determine optimal CI for each specific sensor.

Moreover, the average duration of uninterrupted operation for many modern technical objects grows. At present, for some objects of high duty application the duration of continuous operation is greater than 10 years.

Therefore, very often customers are not satisfied with the present practice of providing the level of confidence in automatic control system measurements.

Calibrations are expensive, but as reality shows, the most part of the sensors submitted to calibration did not need it. According to various estimations, this share is about 60 to 80%. Taking into account the results of calibrations, the dissatisfaction of the customers grows.

There is an obvious contradiction. It is desirable to calibrate measuring instruments as seldom as possible due to economical reasons regarding interruption of the technological process.

However, unreliable information coming to the automatic control system can lead to failures and large economic costs. In order to prevent such failures, it is necessary to check the state of sensors as often as possible.

It is impossible to solve this contradiction within the frames of generally accepted methods of measurement assurance.

The present situation is indicative of the crisis of conventional methods of assuring the metrological traceability during operation of measuring instruments.

3. WAYS FOR SOLVING THE PROBLEM

Attempts to change the form of calibration during sensor operation are made.

Temperature sensors can be considered as an example. In [6] it was proposed to embed a cell containing a fixed-point material in a thermocouple sheath. When a measuring temperature crosses this fixed point, temperature of the sensor is stabilized and the automatic calibration (self-validation) is carried out.

Authors of [7] recommend to design the thermocouple sheath with an additional hole and to insert there a thin reference thermocouple periodically.

It is not hard to show that such attempts to solve the problem can not resolve the reason for the crisis.

Thermocouple with the fixed-point cells enables calibration within the time interval that cannot be shorter than the technological cycle duration. In many cases, this interval is rather long. For example, in a nuclear reactor of the nuclear power plant it is not less than 1.5-2 years.

The fixed-point cell increases the mass of the sensor, therefore the response time of the thermocouple increases. In case of γ- radiation, the error increases due to additional heat.

Calibration of the temperature sensor by the periodic insertion of a thin reference thermocouple into a sensor leads to additional load for personnel. Such procedure may be accompanied by bending and breaking of the reference thermocouple or its displacement from the required place. All this may result in the calibration errors.

Both of the above mentioned proposals do not enable controlling the metrological health of the sensor during the CI.

The attempts to preserve the conventional approach to assuring the reliability of measuring information coming from sensors seem to be unpromising.

At the various stages of the life cycle of a sensor, the purposes of metrologists' activities are different. Therefore, the corresponding methods applied can be different.

The purpose of the initial calibration of a sensor just after manufacturing is the specification of the "normal condition" of the sensor.

At the stage of operation, the purpose is different. It concerns the determination of the deviation of the sensor parameters from those defined at the initial calibration and correction of them, if possible.

At the stage of "the revolutionary situation" in metrology, in order to find possible ways to resolve the crisis, it is necessary to have a criterion. If we accept the analogy between the evolution in Nature and engineering [8-10], then the harmony of one of the ways with the trend found in Nature can serve as such a criterion.

Mr. K. Popper noted that all the organisms are solvers of the problems, problems are born with the appearance of life, and evolution selects the best decisions.

With the "purpose" to prolong the lifetime of developed biological living organisms at the early stages of evolution, Nature "applied" conservative protective methods such as forming sheath, skin, shell, etc.

In order to provide safe functioning of a sensor the same way is applied: reliable sheath is used.

However, if the lifetime of living organism is growing, the number of various dangers increases due to shifts in life conditions. Conservative methods could not provide the necessary grade of the protection of the organism. With the "aim" to weaken the influence of regular temperature and light cycles, Nature "applied" the adaptive methods: the adjustment of the insulating properties of an animal's fur or change of the velocity of physiological processes depending on the season or the time of the day.

Similar methods are applied in measurement technique: due to active thermoregulation under changing temperature, a sensor is keeping its metrological characteristics longer.

The modification of the oxygen metabolism rate while changing the animal physical activity and the stabilization of the conversion gain of a measuring instrument by introduction of negative feedback also can extend the lifetime of biological and technical "complexes" in "healthy state".

The highest form of the adaptive ability of the living organisms with the long term lifetime was provided by intelligence.

The development of intelligence related to solution of the problem of how to preserve life under:

- growing speed and variety of environmental changes,
- increase in the probability of organism failure,
- emerged necessity to forecast and to avoid future threats [11, 12].

During the process of evolution, intelligence turned out to be the most powerful factor for enhancing the survival of biological systems under changing conditions.

As the ultimate purpose of intelligence is to ensure the survival of a "biological complex" during long term interval, the purpose of artificial intelligence in a technical complex (a sensor) should be to assure reliability of measurements during the extended lifetime without metrological maintenance.

It should be noted that the idea to apply "intelligence" in order to enhance reliability of measuring information formed by technical complexes appeared and was started developing approximately at the same stage of technical evolution when it became possible to increase structural complexity of sensors and when it became necessary to extend significantly the sensor lifetime without metrological maintenance.

During long term operation, various potential defects of sensors can be revealed which were not noticed at the stage of sensor manufacturing. Such failures may be caused by wear or external factors. The uncertainty components due to applied measurement method and related to unexpected change of measurement conditions may also appear.

Accordingly, the attribute "intelligent" with the respect to a measuring instrument of any kind should be associated with the ability of this instrument to contribute actively in prolonging its functioning in "metrologically healthy state".

Intelligence in Nature evolved in two ways: formation of "collective mind" of many living organisms and development of the intelligence (mind) of a separate individual.

If the risk of extinction of the "biological complexes" is large, the "collective mind" provides preservation of the experience gained and support of the life of the species as a whole.

A representative example is the life of swarming insects, i.e., bees, which detect the reliable information by "voting". The validity of information obtained by scout bees depends on the number of bees obtained this information [13].

By the way, the appearance of the "democratic method" of estimating the reliability of information of vital importance illustrates a cybernetic approach to evolution, [10, 14, etc.], confirming its efficiency.

Formation of the "collective mind" is a typical example of meta-system transaction representing the integration of a number of autonomous subsystems of a lower level (they can be different, to some extent) and origination of the additional control mechanism at a higher level.

Similar approach to the control of the reliability of information is applied in metrological practice.

At nuclear power plants, sensors, the number of which is redundant, are integrated in a system [15]. The sensors, in which a metrological fault occurred, can be detected on the basis of deviation of their signals from the signals of the larger group of the others included in the system. Information from the larger part of the sensors is considered to be reliable (valid).

The system providing an estimation of the reliability of measuring information formed in the system through the automatic check of metrological health of the sensors included in the system can be called "intelligent".

However, it is not always possible to form significantly large "swarm" of sensors to measure the same value.

The result of check of "metrological health" in the system of the sensors measuring different, but correlated values of the same quantity or of various quantities has a special uncertainty component concerned with the measurement method. Its value depends on the accuracy of the relationship between the values of measurands. Sometimes, this uncertainty component can be greater than the permissible measurement uncertainty of each sensor in the system.

It is possible to decrease the mentioned uncertainty component by equalization of the fields of measurands and influencing quantities. However, the process of equalization of the field requires a considerable amount of time, as well as costs, particularly, if it is necessary to measure several points of the measurement range.

Moreover, information coming from the large groups of the sensors which comprises the "swarm" can be equally distorted by the external factors. Signals from a significant part of the "swarm" may come with some delay that can lead to error decision, etc.

While designing the measuring system, the "swarming" model is not the most effective for creation of the measuring information reliability check.

By the way, the selection of reliable information on the basis of the "swarming" model turned out to be not the most effective method of the biological evolution either due to insufficient flexibility.

The intelligence of an individual living creature was developing with increasing duration of its life. The intelligence has been formed within the frames of a meta-system transaction, which happened as a result of integration of a number of autonomous nerve structures. Each of the nerve structures was linked with one or several sensing elements and had individual features.

In comparison with the "collective mind", intelligence of an individual has an advantage with the respect of the search of the effective ways of survival under changing environment.

The best type of the "sensors metrological parameters" check can be found in a man and other living creatures with developed individuality. For them, each sense-organ, besides the minimum necessary "sensors" of the quantity that is measured, is provided with additional sensing elements. The brain forms a special brain mechanism of testing the stability of vital activity characteristics. This mechanism, known as an "error detector", was discovered by the famous Russian academician N. Bekhtereva [16].

A man diagnoses a "malfunction" of his organs of sense, i.e., an eye or an ear, in the first place, through the unpleasant sense caused by the signals coming from these additional sensing elements. It should be noted, that such additional sensing elements are not required for the video- or audio-information perception and in this sense, redundant.

Using the analogy with the sense-organs of intelligent living creatures, the sensor that we call "intelligent" has the following features:

- it includes one or more basic sensing elements as well as additional elements (additional sensing elements can be such elements);
- the combination of all the elements enables to form a measurement signal as well as additional signals;
- these signals contain information about the metrological health of a sensor (the metrological self-check can be performed);
- processing of measurement and additional signals is carried out by microprocessor, that can be installed inside or outside of the sensor.

Additional ways to reveal the decline in individual sense-organ functioning are:

- the analysis of video-, audio- and other information, coming through all of the sense-organs,
- the response of the other members of society.

In other words, for living creatures with developed intelligence, the "swarming" model of control of the measuring information reliability is "applied" both in the "swarm of sense-organs" and in the "swarm of individuals", but it is only a supporting instrument.

Thus, in biological evolution, two types of intelligence considered above exist, sometimes they supplement each other, but the intelligence of an individual has gained a priority and the greatest pace of improvement.

For providing the vitality of either biological or technical "invention", its cost including cost of operation should be less than the "price of a "useful effect".

It was shown in [17] that the economic efficiency of intelligent sensors is significantly higher than the economic efficiency of intelligent sensor systems.

In the human society, the "collective mind" plays a stabilizing role. The same role it performs in measuring instruments and systems which have artificial intelligence.

The likeness of technical and biological evolution in the development of sensors and the "elaboration" of sense-organs is confirmed even in small details.

According to [14], the intensity of gene mutations is changing with time: if the gene gets in a new environment, the intensity of mutations grows, while under a stable environment it keeps practically unchanged.

The intensity of changes in the sensor evolution is similar to that. The appearance of the new sphere of sensor application with new requirements causes fast growth in theoretical research. A wave of patents and industrial developments targeting improvements in obtaining of reliable measuring information appears after that.

In the period of stabilization of industrial development, situation is different. Sensor manufacturing technologies are improving. However, only rare researchers keep the interest in search of new approaches to the assuring the traceability of measurements.

The block-module principle of organization and development of molecular genetic systems shows that the new systems were formed from blocks (modules) bottom-up. Functioning macromolecular components played the role of such modules [14].

The process of development of adaptive and intelligent sensors is similar to that. Known components (the group of sensing elements and additional elements, analog-digit converters, a microprocessor, etc.) are combined according to the block-module principle.

The similarity of biological and technical evolution gives the basis for forecasting the future trends in the sensor development.

For example, one should expect a development of self-studying sensors with automatic self-check of "metrological health". Such sensors will be able not only to correct the consequences of "ageing" and outside impacts, but to change their parameters automatically on the basis of the predicted changes. This can enhance the reliability of the measuring information formed by the sensors even more.

In technical complexes of high duty application, intelligent sensors with automatic self-check will be joined in the system with "collective mind".

The methods of a Metrological Diagnostic Check (MDC), which are associated with the methods of "embedded" man's sense-organs control, have been developed at the D.I. Mendeleyev Institute for Metrology (VNIIM) since the early 80's [18-20].

The MDC is based upon the designed-in redundancy of a sensor structure or its signals.

Such redundancy allows to form and monitor signals or parameters which depend differently on the factors that give rise to the "most dangerous" error components (i.e. predominant components or those tending to rise quickly). If the method of the MDC is characterized by sufficient sensitivity, this gives an opportunity to inform an operator about the initial stage of fault development (to give a signal like a "pain syndrome"), to correct the sensor parameters in some situations, to forecast its lifetime, and even to provide fault tolerance.

As the developments of the VNIIM have shown, the MDC on the basis of the introduced redundancy can be applied to pressure, temperature, position sensors (with small or large displacement), as well as to some other sensors. In particular, the MDC was used in the system for measuring position of a control rod in a nuclear reactor. This measuring system was designed for WWER-1000 nuclear reactors and comprises a sensor which can operate inside a primary coolant circuit up to 60 years without calibrations [21].

Scientists in the UK, USA, and Germany are successfully dealing with essentially the same problem in respect to flow meters and some other instruments [21-25, etc.].

It should be emphasized that the MDC does not contradict calibration, but supplements it. The MDC enables to enhance the CI of sensors significantly and in a number of cases to increase it up to the lifetime of the equipment where the sensor is embedded.

The interest to the problem of automatic metrological self-check is growing in the world. In order to estimate this growth, a special bibliographic research was carried out. Using SCOPUS (the system for searching scientific information), statistic data characterizing trends in development of methods and instruments for automatic self-check of sensors were obtained.

The search was done on the basis of the sources of information on physical sciences (more than 5500 titles) including books, scientific journals, proceedings of conferences, reviews, patents, etc. for the period from 2002 to 2007 years.

Since at present a standard term for such sensors does not exist, the search was done for the following key words:

1."self-calibration" OR "self-validation" OR "self-diagnostics",

2. "sensor" AND "calibration" NOT "self-calibration",

where AND, OR, and NOT are logic functions.

Fig.1 illustrates the results of the search: it shows the time dependence of the factors characterizing variation in the level of attention to the problem of metrological self-check of sensors.

These factors were calculated according to (1) and (2).

$$a = 100\, n_1/n_2 \quad (1)$$

$$b = 100\, n_{1p}/n_{2p} \quad (2)$$

where a – value characterizing the total number of patents and scientific papers searched out, %,

n_1 - the total number of patents and scientific papers searched out, which contains key words of item 1,

n_2 - the total number of patents and scientific papers searched out, which contains key words of item 2,

b - value characterizing the total number of patents searched out, %,

n_{1p} –the total number of patents searched out, which contains key words of item 1,

n_{2p} – the total number of patents searched out, which contains key words of item 2,

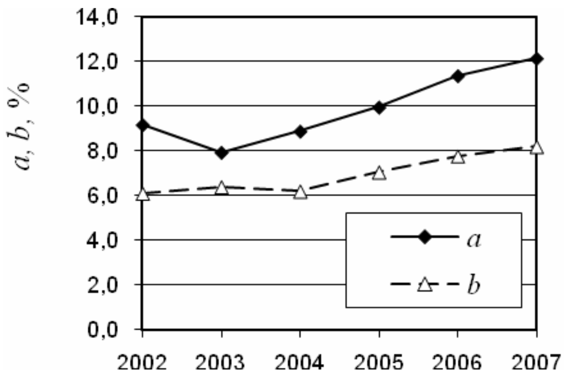

Fig.1. Variation in the level of attention to the problem of metrological self-check of sensors

The relative values as indicators of the search results were used in order to reveal common trends. Such factors depend insignificantly on the number of publications searched.

The graph shows a growing interest in development of the methods and instruments for automatic metrological self-check of sensors in last years. Approximately since 2005, the growth of attention to the applied inventive developments has been noticed. This is natural, because the new microminiaturization technologies and new materials emerged. At the same time, the importance of the problem of assuring the reliability of measurement information coming from sensors is growing year by year.

Under globalization of economics, the above described trend in development of the sensors embedded in the complicated objects with automatic control systems stimulates development of the unified requirements for a number of metrological procedures, terms, and definitions [26].

First of all, these requirements include requirements for:

- techniques for accelerated tests intended for experimental evaluation of the CI of the sensors with the specified long term lifetime [27];
- sensor operation conditions for which the long term CI is defined;
- quality management system regarding production of such sensors [28];
- methods of assessment of the self-check efficiency;
- methods of forecasting the residual useful life of sensors;
- forms of presentation of the self-check results;
- terms and definitions in this area of metrology.

A number of papers discussing these problems have been published recently. But the difference in views of their authors can lead to development of the sensors with ambiguously interpreted characteristics, which can result in unfair competition and increased probability of failures and accidents.

CONCLUSION

Present-day technologies created a basis for the development and mass production of the wide variety of the intelligent sensors with the metrological self-check. This trend in development of measuring technique is similar to the trend of biological evolution and can assure the traceability of measurements under operation conditions with minimum cost.

With development of the intelligent sensors, their functions are supplemented by additional functions of self-correction, fault tolerance, and forecasting the sensor "metrological health".

Modern level and pace of innovations in the area of the metrological self-check results in the necessity of transition to a new stage in the evolution of metrology. Such a stage is "accreditation" of the instruments, including sensors, with the metrological self-check. For such instruments a long term CI can be specified.

Expected appearance of a wide spectrum of sensors with the automatic self-check, requires combination of efforts of metrologists from various countries in order to develop the recommendations to the manufactures of these measuring instruments.

Enhancement of manufacturing and application of the intelligent sensors with the metrological self-check will cause the growth in demand for skilled metrologists-scientists. This demand is caused by the necessity to perform the creative work of development and manufacturing of the sensors and systems with the metrological self-check.

At the same time, the volume of routine calibrations will inevitably decrease.

REFERENCES

[1] A.J. Wallard, "Bringing Precise Measurement to the Workplace", Proceedings of the XVI IMEKO Congress, pp. 295-298, September 25-28, Vienna, 2000.

[2] T.S. Kuhn, "The Structure of Scientific Revolutions", Chicago, University of Chicago Press, 1962.

[3] A.E. Fridman, "Theory of Metrological Reliability", Measurement Techniques, Vol. 34, No 11, pp. 1075-1091, 1991.

[4] ISO/IEC 17025:1999. "General Requirements for the Competence of Testing and Calibration Laboratories".

[5] OIML D 10. "Guidelines for the Determination of Recalibration Intervals of Measuring Equipment Used in Testing Laboratories", 2007.

[6] F. Bernhard, D. Boguhn, S. Augustin, H. Mammen, and A. Donin, "Application of Self-calibrating Thermocouples with Miniature Fixed-point Cells in a Temperature Range from 500 ^{o}C to 650 ^{o}C in Steam Generators", Proceedings of the XVII IMEKO World Congress, pp. 1604-1608, Dubrovnik, 2003.

[7] V.N. Loginov, N.S.Serov, A.A.Isaev, "Conditions and Ways of Enhancing the Reliability of Temperature Measurements in Nuclear Reactors", Proceedings of the 3rd All-Russian Conference "Temperature-2007", Obninsk, 2007.

[8] S. Lem, "Summa Technologiae", Verlag Volk und Welt, Berlin, 1980.

[9] N. Wiener, "Cybernetics: Or the Control and Communication in the Animal and the Machine", Cambridge, MA, MIT Press, 1948.

[10] V.F. Turchin, "The Phenomenon of Science. A Cybernetic Approach to Human Evolution", New York, Columbia University Press, 1977.

[11] R. Taymanov, K. Sapozhnikova, "Intelligent Measuring Instruments. Maximum Reliability of Measuring Information, Minimum Metrological Maintenance". Proceedings of the XVII IMEKO World Congress, CD 1 0623 20 3030C314, pp. 1094-1097, Dubrovnik, 2003.

[12] R. Taymanov, K. Sapozhnikova, "Intellectualization of the Built-in Measuring Instrument as the Way to Enhance the Reliability of Equipment", in "Problems of Mechanical Engineering: Precision, Friction, and Depreciation, Reliability, and New Technology", ed. V.P. Bulatov, St.Petersburg, Nauka, pp. 421-469, 2005.

[13] D. McFarland, "Animal Behaviour. Psycology, Ethology, and Evolution", Prentice Hall, 1999.

[14] V.G. Red'ko, "Evolution. Neural Networks. Intelligence. Models and Concepts of the Evolutionary Cybernetics", Moscow, KomKniga, 2007.

[15] H.M Hashemian, "Maintenance of Process Instrumentation in Nuclear Power Plants", Berlin, Heidelberg, New-York, Springer, 2006.

[16] N.P. Bechtereva, N.V. Shemyakina, M.G. Starchenko, S.G. Danko, and S.V. Medvedev, "Error Detection Mechanisms of

the Brain: Background and Prospects", International Journal of Psychophysiology, Vol. 58, pp. 227-234, 2005.
[17] A. Pronin, K. Sapozhnikova, R. Taymanov, "Control of Level of Confidence in Measurement Information Passing from Sensors", Datchiki & Systemi (Sensors & Systems) (in publication).
[18] K.V. Sapozhnikova, R.Ye. Taymanov, V.V. Kochugurov, "Metrological Checking as a Component of Diagnostics of Flexible Production Systems and Robotics Complexes", in "Testing, Checking and Diagnostics of Flexible Production Systems" (from the materials of the seminar hold at the Blagonravov IMASH of the Academy of Science in 1985), pp. 269-273, Moscow, Nauka, 1988.
[19] MI Recommendation 2021-89. "GSI. Metrological Assurance of Flexible Manufacturing Systems. Fundamentals", Moscow, Committee on Standardization and Metrology, 1991.
[20] K. Sapozhnikova, R. Taymanov, "Increasing of the Metrological Reliability of Sensors. New Problems and Ways of Their Solution", Proceedings of the 8th International Symposium on Measurement Technology and Intelligent Instruments", pp. 281-284, Sendai, September 2007.
[21] R. Taymanov, K. Sapozhnikova, I. Druzhinin, "Measuring Control Rod Position", Nuclear Plant Journal, March-April, pp. 45-47, 2007.
[22] M.P. Henry, D.W. Clarke, N. Archer, J. Bowles, M.J. Leahy, R. P. Liu, et al., "A Self-validating Digital Coriolis Mass-Flow Meter: an Overview", Control Engineering Practice, Vol. 5, No 8, pp. 487-506, 2000.
[23] V. Hans, O. Ricken, "Self-monitoring and Self-calibrating Gas Flow Meter", Proceedings of the 8th International Symposium on Measurement Technology and Intelligent Instruments, pp. 285-288, Sendai, September, 2007.
[24] R. Werthschutzky, R. Muller, "Sensor Self-Monitoring and Fault-Tolerance", Technisches Messen, Vol. 74, No 4, pp. 176-184, 2007.
[25] Z.Feng, Q.Wang, K.Shida, "A Review of Self-validating Sensor Technology", Sensor Review, Vol. 27, No 1, pp. 48-56, 2007.
[26] K. Sapozhnikova, R. Taymanov, "Development of Sensors Distinguished by Enhanced Reliability", Proceedings of Conference "Nuclear Power Instrumentation, Controls, and Human Machine Interface Technology", Albuquerque, New Mexico, 2006.
[27] R.E. Taymanov, K.V.Sapozhnikova, A.P. Lukashev, A.N. Pronin, "Quality Control in Advanced Reliability Sensors Manufacturing", Datchiki & Systemi (Sensors & Systems), No 9, pp. 67-80, 2006.
[28] Yu. Tarbeyev, A. Kuzin, R Taymanov, A. Lukashev, "New Stage in the Metrological Provision for Sensors", Measurement Techniques, Vol.50, No 3, pp.344-349, 2007.