

## PROBLEMS OF DEVELOPING A NEW GENERATION OF INTELLIGENT SENSORS

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**Abstract** – Modern technological processes require industrial sensors of non-electric quantities, that are distinguished by the highest survivability, increased lifetime and reliability of measuring information. It is shown that intelligent sensors can meet these requirements. Terminological aspects in this field are considered. The main directions for developing a new generation of intelligent sensors are shown.

**Keywords:** intelligent sensor, metrological characteristics, self-diagnostics.

### 1. INTRODUCTION

The problems that concern working-out the requirements to a new generation of microprocessor-based sensors and to the concept of “artificial intelligence” applicable for measuring instruments, have emerged in connection with the necessity to develop “super-reliable” sensors for non-electric quantities. Such instruments are intended to be applied in nuclear power engineering, cosmonautics, defense systems and some other industries. These instruments should be distinguished by permanent operation for multiple years, by the fact that the possibility for an operator to have an access to them is strongly restricted, and by very high requirements for trustworthiness of information coming from sensors.

The sensors under development should operate under changing conditions that include noise as well as in the situation when inner defects occur. They must not require for the regular maintenance works during operation.

At present, microprocessor-based sensors are developed by heuristic methods. The unified terminology has not settled. There has not yet been created any common methodology that would cover the totality of metrological problems related to development, tests, producing, to quality control of technology and to automatic metrological assurance during use.

It is necessary to single out the main scientific problems of the measurement theory, the solution of which will hasten the progress in the area of developing a new generation of sensors.

### 2. PROBLEMS OF DEVELOPING INTELLIGENT SENSORS

#### *2.1. About the necessity to harmonize terms and definitions*

In papers written by different authors, several various terms for the new generation of sensors and their distinctive peculiarities are used, for example, a smart sensor, an intelligent sensor, an intelligent agent, a sensor agent, an intelligent sensor agent, an adaptive sensor, a self-validating sensor, a self-checking sensor, self-diagnostic sensor and others.

Measuring instruments, carrying out operations traditionally fulfilled by a man, i.e., those operations concerned with setting to a zero, choosing a necessary measurement range, applying a correction for an impact of a known influencing factor, in the opinion of authors [1,2], can be referred to intelligent instruments. As estimated in [3], they should be referred to measuring instruments with a small degree of intelligence. According to the point of view given by the authors of [4], they are to be called adoptive ones, whereas the intelligent instruments are only instruments for which a measuring procedure is automatically optimized in compliance with an assumed criterion. As a criterion, it is suggested to assume an error of measurements, while optimization of the measuring procedure is to be carried out on the basis of selection from the whole totality of possible variants.

The term “intelligent”, as applied to a technical system, is used in the field of the control theory. The author of [3] writes that an intelligent technical system is a system with several layers of information processing (from the lowest layer to the highest one): i.e. a certain action, manipulation with knowledge bases and formation of a solution, self-learning, giving out a prognosis and participation in an interactive dialog. Systems characterized by the first two layers are considered to be intelligent systems with a small degree of intelligence, whereas the one characterized by the first three layers is an intelligent system with a great degree of, and the system with five layers is a fully intelligent system.

The authors of [5] use the term “a smart sensor”. It means a programmed measuring instrument that responds to calibration (verification) requests, reacts to

interrogations about its health and trustworthiness of measurement results, and provides error estimations.

If an “intelligent agent” (they mean software of the higher level, which provides the sensor with effective communication with its environment and other sensors) adds it, it transforms into “the sensor agent”. According to [6], an intellectual sensor is a self-validating sensor that gives an estimation of the trustworthiness of each measurement, besides of the estimation of measurement result. In essence, a similar definition is used in [7], where such a sensor is called self-validating, self-diagnostic and self-calibrating.

It is seen from these examples that, on one hand, the same terms can be interpreted in a different way, but on the other hand, different terms are used for the same ideas.

It is necessary to develop international guide on terminology in this field.

Our proposal for this guide relies upon the idea that sensor intelligence should be associated with its most important task. This task can be singled out in the way like S. Lem [8] has performed, by comparing the history of evolution of alive and technical systems.

During the process of evolution, just intelligence turned out to be the most powerful factor of evolution contributing to survival of biological systems under changing conditions. (If the conditions on the anthill are stable intelligence is harmful for an ant). The growth of intelligence is associated both with provision of survival under an increasing speed of the change in the situation and with the need to predict and to take into account dangerous changes.

While the most important task of the intelligence is providing survival of a biological system, the most important task of the artificial intelligence of a sensor is to increase its lifetime (verification interval) when it is in a metrological good state [9]. At the same time, as intelligence is the main form for cognition of the reality [10], the intelligent sensors must have the ability to perceive and process additional (redundant) information (we mean here the information that is additional in comparison with non- intelligent sensors). This statement has something in common with [6], where the near-term outlook is associated with creating the “sensor agents”, which can survive in the dynamic environment on the basis of information perceived from the outside. Therefore, it is suggested to consider the presence of redundancy that provides metrological self-diagnostics and self-correction (we include here the case when a defect in a sensor occurs) as the main attribute of the intelligent sensor.

The term “metrological self-diagnostics” of a sensor is suggested to call the automatic check of stability of the metrological characteristic that had been assessed at the previous verification.

The term self-correction of a sensor is suggested to call the automatic decrease of the error that arises both due to external factor impacts and due to aging of sensor components or a defect in the sensor. At that, in a number of cases self-correction can be made with the

accuracy (or trustworthiness) that is reduced, but acceptable for a customer.

The ability of a sensor to keep metrological characteristics within the permissible limits is recommended to call “survivability”.

The suggested interpretation of the above terms is used below.

## *2.2. Control of the sensor parameter stability at the stage of check-out of manufacturing operations*

Applying the artificial intelligence to a sensor is a necessary, but insufficient measure to increase significantly the verification interval. Money on intellectualization of sensors that often become disabled is not justificatory.

The problem arises how to check if the quality of sensor manufacturing is appropriate to the requirement for providing the verification interval of many years.

In our opinion, this control must provide for detecting the weak points of construction and technology that can cause deterioration of metrological characteristics of the sensors after many years of use. Such control must be based on the results of investigation of the sensor degradation processes that are individual for each type of sensors and on accelerated tests of sensors. The distinction between these tests accompanying with the subsequent metrological analysis and the traditional quality control are as follows.

- The purpose is to check if the tests resulted in some signs of the processes causing the error increase.
- The sensitivity of measurements should allow revealing the error that is much less than the permissible error stated in the specifications for the sensors.
- The defect of technology or construction is singled out on the basis of error changes, i.e. the value of the time- or impact cycles number derivative of the error under tests.
- Identification of the defect of technology or construction is carried out taking into account information about degradation processes.]
- The criterion that the construction and technology are acceptable for the subsequent tests intended to assess the sensor lifetime is stability of the error (within the conventional permissible limits) for each sensor in the tested set. These limits are stated on the basis of the hypotheses about the dependence of the sensor error and time during the sensor lifetime.

A plan of the accelerated tests should be formed taking into consideration the international experience.

## *2.3. Forecasting the sensor lifetime*

This problem is associated with the previous one. It concerns the procedure of carrying out the accelerated tests and making the forecast on its basis. The common peculiarity of this problem and the previous one is the fact that intelligent sensors are produced at present only in small-lot production. Therefore, as it

was in the case described before, tests should be based on the number of sensors that is small, while the time period for testing is comparatively short.

The known documentary standards and guides concerning the accelerated tests, do not include such cases. The peculiar questions are as follows:

- detection of the load spectrum that is characteristic for the real working conditions of sensors;
- determination of the typical load spectrum that can act in cycles and provide for the necessary forcing coefficient;
- assessment of the non-dimensional gamma-percentile life;
- ascertainment of the dependence of the forcing coefficient and the acceleration coefficient;
- estimation of a sensor lifetime.

These tests are specific and several different approaches to their arranging can be applied. Therefore, it is possible that the obtained estimations of the sensor lifetime will have a considerable dispersion due to the methodical error.

In order to obtain the comparable results assessing the long term reliability of sensors that are produced by different enterprises it is necessary to develop international guides that will include test procedures for estimation of the sensor lifetime and gamma-percentile life.

#### *2.4. Methods related to metrological self-diagnostics of sensors*

One of the determinative features of an intelligent sensor is the automatic metrological self-diagnostics. (If the diagnostics is accompanied by estimation of measurement quality it can be called self-validation).

This feature can be realized by two different ways. The first one is embedding calibrators or additional sensors, which are more accurate [11-13, 7]. The second way is associated with a comparison of several signals or parameters that are close in accuracy, i.e. they are equivalent in a metrological sense. The latter method we call the metrological diagnostic check (MDC).

Embedding the calibrator in a measurement instrument, as a rule, can worsen parameters of this sensor. At that, the frequency of calibration is limited by the technological process.

For example, a cell that contains a fixed-point material is embedded in the thermocouple sheath. Self-validation is carried out when the temperature crosses this fixed point [11,12].

However, self-validation made only in one point does not prove that the metrological state is good in the whole measurement range. The time interval between such self-validations can not be shorter than the technological process allows it. As a result, the error of the sensor can increase dramatically during this interval. At that, the inertness of the thermocouple can worsen.

Application of a set of materials [11] and a heater [12] can partly take these problems away.

However, embedding calibrators in measurement instruments (in particularly, in sensors) is possible only for some measurands.

When measuring, practically, any non-electric quantities it is possible to embed additional sensors in the same case. These sensors can measure the same measurand, but have the higher accuracy. At that, self-validation can be carried out as often as necessary. For example, it was suggested in [13] to use a platinum resistance thermometer connected in series with thermocouples. Using this device it is possible to carry out self-validation of the thermocouples at any stationary temperature interval as often as necessary, but the inertness of the thermocouple is worsen.

However, it is impossible to guarantee that the metrological state of the "reference standards" - embedded calibrator or additional sensor (that is more complicated than the checked sensor)- will be good for many years [14, 15]. Therefore, in fact, some of described methods should be considered as the MDC.

The metrological diagnostic check is often carried out on the basis of triplication of the identical sensors. At that, the trustworthiest value is considered to be the value, which is the average of three values or of two values that are almost the same. In the latter case the third value is rejected.

However, for series-produced sensors of the same type, a drift of metrological characteristics in the same direction and with a close speed is the most probable [9, 14]. If the triplication of the sensors is used this systematic error can not be revealed. The drawback is also in the necessity to place a triple number of sensors, which, in many cases, is impermissible by an argument of engineering limitations.

The authors of this paper consider the approach [9, 16], that is leaned upon the circumstance that reasons for the error increasing outside the tolerance limits are far from being equivalent. They can be classified for each sensor type by probability of occurrence and grouped by attendant indications.

The automatic check of stability of metrological characteristics is carried out by estimation of "dangerous" error components, i.e. predominant ones or tending to a fast growth.

(An analogy to confirm that the sensor provided by MDC function has the intelligence: a man perceives and feels a violation of his organism normal functioning by a limited number of features, but this has turned out to be enough for survival and priority development of the mankind).

The MDC is admittedly limited: it does not react to certain error components. However, because of the sensitivity to the most dangerous error components and also by virtue of a sufficiently frequent realization, the MDC application reduces the risk of giving unreliable information to a customer.

As in the case with verification, the positive result of the MDC cannot give 100% guarantee of metro-

logical serviceability of a measuring instrument. (As an analogy: a person's normal state of health or even results of the clinical checkup does not exclude probability of his sudden falling ill or even of death).

However, the fact should be taken into consideration that if verification is carried out all error components are assumed to be sufficiently stable during a rather long verification period. In the MDC case we are dealing only with that part of them, which has been selected upon the basis of the results of a preliminary investigation. It is reasonable that in this case it is tolerated to increase dramatically the time interval during which stability of this group of error components can be expected (ideally, up to the lifetime of the equipment where the sensor is embedded).

This approach means that the necessary for the MDC signals or parameters can be obtained from the inside, by using informational redundancy of the sensor and from the outside by using redundancy of measurement information or by the use of their combination.

In developing an intelligent sensor intended for a multi-purpose application, it is impossible to lean upon a priori measuring information, which depends on concrete destination of the instrument under development and the peculiarities of the specific technological process.

Therefore, in this case the redundancy induced inside the sensor is applied. Most of all, it is provided using the structural redundancy that is induced in a primary transducer of the sensor. (It is natural: development of intelligence in animate nature also was accompanied by development of organs of sense).

A capacitance sensor of distance to a contact surface [17] can be considered to be an example. It contains, at least, two electrodes displaced in the same case at a known distance. This makes possible to obtain two different characteristics of transformation. The MDC is realized by checking a relationship between output signals from the both electrodes.

Similarly, in a measuring instrument of positioning a metal cutting tool, errors caused by impurities and separation of scale rules were revealed using two reading heads rigidly connected between each other and spaced along the space rule [18].

(An analogy: all the organs of sense have redundancy. For example, we have two eyes and two ears. These organs of sense are not the duplicates; they are mutually complementary).

The redundancy of measuring information (the redundancy from the outside) means the presence of knowledge about permissible limits of variation of input signal parameters, as well as about known correlation between values of the measurands and so on.

When developing the sensor that is intended to be mounted in the specific equipment the redundancy of measurement information can be useful.

In particular, the redundant information can be obtained if the time interval between measurements is

made shorter than the interval that is appropriate for carrying out the main measurement function.

An example is a flow meter [19]. It is suggested to identify its faulty state when the output signal fluctuations increase.

Another variant of the redundancy of measuring information is applied to an intelligent measuring instrument [20] developed under the authors' supervision. Several samples of such an instrument are embedded in a nuclear reactor. This instrument is intended for determination of position of a control rod.

One of the MDC methods used in it is the check that the codes of the neighbor positions are appropriate to the specified scale code.

A number of the metrological self-diagnostic modes have been used for many years. The national documentary standards [21, 22] have been published in Russia and the UK. Attempt to systematize such methods were made, for example, in [23, 24]. Nevertheless, designing of self-validating sensors is still carried out by heuristic methods.

In order to pass on the algorithmic designing of such measurement instruments the algorithms for computer-aided design should be elaborated. It could be similar to the algorithm of creating inventions.

#### *2.5. Methods related to self-correction and support of survivability of sensors*

As it is for the MDC, the possibilities for self-correction depend on the redundancy from inside and outside. The simplest method for self-correction in presence of transient errors is frequency or time filtration.

However, if a faulty state of a sensor is at the bottom of the increased error of a measurement result, to provide for sensor survivability the algorithm of data processing must be changed automatically. At that, localization and a character of the metrological defect obtained on the basis of diagnostics results should be taken into account.

For example, the MDC notices an abrupt change in an input signal while such variation cannot take place in the technological process. Then, registering the fact of a faulty state and giving information that the reliability has been decreased, the sensor can correct its measurement result.

In the intelligent measuring instrument [20] if a defect occurs in one of sensitive elements (that is an inductance coil) the false code characterizing the position of a nuclear rod appears. The position of the rod can be corrected taking into account the number of steps made by the rod from the nearest position that had a true code.

However, for the most part of the displacement range it does not require: due to the redundant number of the inductance coils used in the sensor the code combinations give true information about the position of the nuclear rod when any single defect occurs.

In such situations an ability of the intelligent sensor to estimate automatically a grade of decreasing the reliability of measuring information is important.

To evaluate exactly the grade of the uncertainty increase is not possible in many situations.

For the considerable part of applications it is possible to use an estimation of quality of measurement results. It was proposed in [24] to generate the measurement value status (SECURE, CLEAR, BLURRED, DAZZLED or BLIND) and to assess the level of maintenance action currently requested by the sensor (NONE, LOW, HIGH, CRITICAL).

The idea to show to the operator the necessary level of maintenance actions was also independently realized and described in [20,7] and some other systems.

So, an intelligent sensor that has sufficient redundancy is capable to give a signal to the staff when defect appears and to wait for assistance maintaining capacity for work.

(By analogy with the living organism it is possible to say that these capabilities characterize the ability of an intelligent sensor "to feel poor health" and to take the necessary precautions).

To increase the efficiency of elaboration of sensors with increased survivability it is necessary to develop the theoretical basis for their designing. It can be elaborated leaning on the methods of noise-immune transmission of information used in telecommunication.

### 2.5. Forecasting the residual useful life of sensors

During the use it is important to know the time interval, that gives an opportunity to consider measurement results to be trustworthy. A forecast of the residual useful life should be done automatically on the basis of data obtained by the subsystem of self-diagnostics.

In order to achieve this purpose it is worthwhile to process the diagnostics results at two levels, i.e. at short and at comparatively long time intervals. So, a drift of inherent parameters of a sensor can be revealed. Integration of separate intelligent sensors into an intelligent system can also serve this purpose. It will give the opportunity of forming a multi-dimensional image of a physical field characterizing the state of parameters of a technological process and to single out tendencies in its change.

On the basis of these forecasting estimations the sensor can initiate an interactive dialog with an operator and "suggest" him the necessary measures on preventing a defect.

The corresponding algorithms are used in the intelligent sensor [20] that has been working for many years at the nuclear power plant in Russia.

However, the fact that the particular solutions exist does not take away the necessity to develop standard methods for predicting the residual useful life of various sensors.

### 2.7. Development of the databases that provide for elaboration of intelligent sensors

In order to increase the efficiency of intelligent sensor designing it is necessary to create the databases concerning:

- dynamics of sensor error changes during the long-term interval, taking into account the working conditions;
- physical and chemical process leading to the growth of the dangerous error components of sensors;
- test procedures that can single out the sources of the error growth under manufacturing;
- methods for self-diagnostics.

### 2.8. Improvement of mathematical support for development of intelligent sensors

Elaboration of intelligent sensors requires for development of the mathematical apparatus that is necessary for sensor designing and operating:

- methods related to forecasting the sensor lifetime;
- mathematical methods that stipulates for increase in survivability of sensors;
- modelling methods to simulate sensor functioning under changing conditions and if a defect occurs;
- methods related to the joint processing of qualitative and quantitative estimations at the MDC and to interpretation of measurement results and the other problems.

International cooperation could play a large role in solution of the problems mentioned above.

## CONCLUSIONS

The sensor provided with automatic self-validation and being characterized by the increased survivability, to the utmost, corresponds to the concept of the intelligent measurement instrument. The need of industrial enterprises for intelligent sensors is increased quickly. In order to meet this requirement a number of scientific problems pointed above. should be solved.

Investigations in this direction are carried out in the Mendeleyev Institute for Metrology (Russia) and in several centers in the other countries. There is a necessity to extend considerably the international cooperation in this field.

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