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Metrological Array of Cyber-Physical Systems. Part 5. Quality Assurance in Measuring Instrument Design

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Abstract: Possibilities of quality evaluation of measuring instruments for Cyber-Physical Systems are studied basing on their objective functional properties. It was proposed to apply the Shannon–Hartley theorem for noisy channel and Hartley logarithmic measure in the selecting, transmission, transforming the measuring signals and defining the amount of measurement data. To ensure the particular level of measuring instruments quality at the design stage due to auto adjustment of errors, the required conditions are researched. The terms of automatic calibration and metrology verification of measuring instruments in situ are considered. *Copyright © 2015 IFSA Publishing, S. L.*

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1. Introduction

Built-in measuring instruments (hereinafter MIs) are the integral part of Cyber-Physical Systems (CPS). Since such MIs contain ADC and DAC and they have to work with predetermined metrological performance during the whole operating period; there is a task of their periodic metrological checking, verification and/or calibration. Their input signals can be heterogeneous electrical and nonelectrical quantities.

Realizations of metrological verifications is linked with chain of technical and technological problems because these built-in units are dispersed and their output signals can be used to verify the state of CPS (Fig. 1) [1-2]. Objective information about technological processes running is obtained by the way of measuring that is considered as entire process from the perception and transforming of the object measurement information to its processing, saving, transmission and usage with the aim to elaborate retroaction at controlled objects. Therefore it is reasonable to study possibilities of smart MI realization to fulfill the function of operational control of CPS measuring channels in working conditions of the operation.

2. Shortcomings

Nowadays the number of built-in measurement instruments is sufficiently large with tendency to considerable increase in the future [1-2].

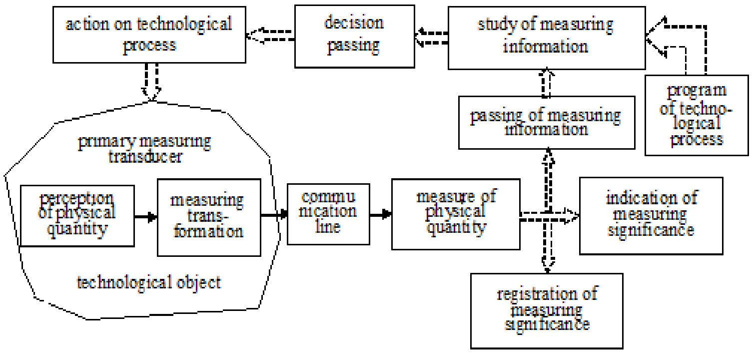

Fig. 1. Functional scheme of modern measuring instruments

Given this and taking into account their dispersion the issue of metrological assurance optimization becomes an urgent task. Taking into consideration tendencies of CPS designing as distant dispersed applied infrastructure it is practically impossible to use traditional procedures of the metrological verification [3-8]. Requirements for measurement precision can significantly differ for every concrete measurement task but all these tasks must be performed with ensuring of tracing [9-14]. Given the large number of types and mass of used MI and labor-intensity of metrological procedures in modern measurement systems, tracing of physical quantities measurement is not always ensured as normative documents required [12-14]. Another important aspect of CPS metrological providing is an achievement of necessary precision and metrological reliability of measurements performed in the working conditions of the operation at all stages of producing (for instance, microelectronic production) [7-8, 15-16].

Significant quantities of cheap MIs are proposed in the market that substantially complicates the problem of the CPS designing [1-2, 17-18]. Simultaneously one of the central problems is quality estimation of measurements performed by means of MIs. It predicts the ascertainment of MIs capabilities, correct choice of the indexes list and determination of ponderability coefficient values during the measurement quality estimation. Therefore the problem of the performed measurements quality estimation is not solved in theory and in practice [11-14, 15-16].

Furthermore at the stage of MI design there are no theoretical and practical recommendations regarding providing of necessary level of MI quality in conditions of the operation. Today international metrological organizations recommend using the conception of the uncertainty of received results as the main standard of performed measurements quality [19-21]. By this way it was attempted to eliminate the basic practical defect of measurement errors approach as difference between measured and true value of measurand.

However during designing it is sufficiently difficult (or impossible in general) to use the uncertainty approach because the measurement results are still absent. But in this case the measurement error approach can be successfully applied taking as true the nominal value of MI transformation coefficient (function). Logically to suppose that it is the value which the designed MI measurement result has to tend to.

3. Aim of Research

The aim of the article is to determine at the stage of designing of theoretical basis and practical recommendations regarding providing the necessary quality level of MI in operation conditions.

4. Theoretical and Applied Researches

Traceability, accuracy, precision, systematic bias, evaluation of measurement uncertainty are critical parts of a quality management system. Basic provisions concerning metrological support of the development, production, testing and operation of MI used during goods producing, science researches conducting and other kinds of activity are regulated by the number of international standards. These standards establish general requirements for measurement processes and equipment, the order of its usage and competence of testing and calibrating laboratories [12-14]. The technical basis of metrological assurance involves the systems of national and working standards of physical units, standards, comparators for transferring dimensions of physical units, certified reference materials and substances standards component pattern and characteristics of substances, and working MIs.

4.1. CPS MIs Metrological Assurance

In many countries metrological verification and calibration of MIs are performed on the ground of special testing schemes which documentarily establish the tools, techniques and exactness of transmission of unit dimension of particular value from national to working standards.

For MI metrological verification it is used the methods of direct comparison of tested MI with the standard mean of the same type, and also direct verification by the tested MI of output signal of multi-valued measure and determination of the uncertainty as difference of measurement results. Furthermore sufficiently precise portable multivalued code-operated measures can be used too and it provides the possibility to perform operative metrological control of MIs in the operation conditions.

In the accordance with normative documents the MIs verification is performed in the laboratory where there are special (normal) conditions including the absence of hazardous radiation, interferences, impact loads, vibrations which can affect MI parameters.

Metrological verification fulfillment demands the dismantling of instruments from technological objects and transportation them to laboratories. In addition to only technical, organizational inconveniences and financial expenditures the MI verification in such “hothouse” conditions doesn’t meet a lot of metrological aspects of their operation. Besides, other units of measuring circuit of technological MI are not verified (Fig. 1). The verification of the whole measuring systems in laboratory environment is meaningless because it demands the dismantling of this system.

It is reasonable to revise traditional verification methods and techniques for virtual systems of gathering and processing of measurement data in the direction of automation. Economically expedient seems to conduct verification in place. To accomplish it portable code-operated measures of physical values and development of proper software are required. This enables to enhance significantly labor productivity [22-23].

4.2. Continuous Control of Measuring

One of the main important MI parameters is their metrological reliability. For its providing on proper level there is a need to control measurement processes continuously [12]. Reliable measurement information of necessary exactness can be received only by the way of technically well-grounded choice of MI that includes next data [22-23]. Firstly this is the list of measurement parameters of the object with permissible measurement errors. Considering the stochasticity of the analyzed processes it is necessary to know acceptable probability of false and unidentified failures for every controlled parameter, values of confidence probabilities, distributing laws of the measured parameters and their measurement errors. MI operation conditions affect significantly their metrological properties or properties of their elements. These are mechanical loading, climatic effect (temperature, humidity, pressure etc.), and presence/absence of the environment (corrosive gases and liquids, high temperatures or voltage, fungi, mold, electromagnetic fields, radioactive and other emissions).

Then after determining restrictive characteristics precision characteristics (permissible limits of basic and additional errors) of MI are estimated. Reliability of the measuring parameter indicates at probability that measurement error value will not exceed permitted values with given probability $P(\Delta_\Sigma \le \Delta_{allow}) \ge Đ_{conf}$, where P is the actual value of the probability, Δ_Σ is the total error of result obtained by selected MU, Δ_{allow} is the boundary value of measurement allowable error, P_{conf} is the set value confidence probability. Reliability is ensured if the probability of false and unidentified failures on results of monitoring parameters by selected MIs does not exceed a specified level: $P_f \le P_{fal}$; $P_{ui} \le P_{uial}$, where P_f, P_{fal}, P_{ui}, P_{uial} are the probabilities’ actual and allowable values of false and unidentified failures respectively.

Probabilities value of false and unidentified failures by the measured parameter, measurement error and tolerance for the controlled parameters are theoretically examined in [22-23] and described by complicated expressions.

The method of simplified calculations leads to overstated demands regarding precision of chosen MI. For practical realization of mentioned method there is a need of quite significant amount of a priori information about stochastic properties of measured parameters X_i, and also about MI transformation functions. Mainly such information is absent. To receive this information it is necessary to conduct plenty of studies. Moreover under drastic changes of any measurement conditions (for example, emergency conditions work and electromagnetic induction) crude errors appear that decreases measurement reliability significantly. Incremental degradation changes of MI components and units in some time lead to appearance of noticeable uncertainty or even to MI metrological failure within intercalibration interval. Today there is no theory of the determination of this interval duration which mainly is determined on the experience basis of similar MI operation and on “engineering intuition”. For this reason the standard ISO 10012:2003 recommends to implement methods of the control of measurement processes based on regular verification and gradual analysis of measurement results. The mentioned approach should be applied at all measurement stages: from standards calibration by state metrological laboratory to own regular verifications [12]. In practice the measurement process control is applied with the aim to enhance the safety of technological process (f.i., of energy plants) or providing of guaranteed quality of final product. The metrological management system ISO 10012:2003 has to guarantee that measurements (performed with usage of measurement equipment within intercalibration interval) is quiet precise for given problem. But MIs are checked metrologically for ultimate consumer of single models or small samplings of their general totality.

The distribution law of the measured parameter for totality of MIs, which are given on periodic verification, differs considerably from the distribution law of the same parameter at the moment of MI release from producing and practically it cannot be studied [22-23].

5. Measuring Instruments Quality Estimation Methods Improvement

MI operating conditions complications and different nomenclature of their parameters complicate the quality analysis. Its ultimate aim is close to optimal (in coordinates "functionalities - cost") choice of MI which is necessary for current measurement task from all variety of modern devices.

To ensure required quality level of goods, production and services produced with MI application the normative documents recommend to perform control of measurement processes as separate long procedure [12-14]. Traditionally to estimate any production quality of the same kind differential, complex and mixed-mode methods are applied. The differential method includes such shortcomings as some subjectivity and insufficient precision of quality coefficient determination [16]. While using of complex method it is necessary to choose natural generalized quality index for this kind of production and to determine its functional dependence from main single indexes that partly affects the quality. During estimation of such complex technical production as MI mainly mixed method is applied. This method is based on the exarticulation of the number of separate groups which include MI significant properties. For this MI generalized quality complex indexes are determined with following their comparison with the help of the differential method concerning appropriate indexes of basic MI [16].

General peculiarity of such product as MI is that technical and economic indexes can be differently characterized depending on the type of measured value and these indexes can be changed at all stages along life cycle that includes designing, producing and operation. Now operation expenditures that mainly connected with expenses on periodic verifications of MIs, their maintenance and calibration [11, 20-24], determine MIs operating time. MIs cost continuously decreases, even for devices of high precision (0.01...0.05 %) because of wider involvement of integrated electronics [1, 17-18].

With regarding to spectra of MI opportunities it is proposed to consider the informational energy efficiency h_3 as functional dependence which connects their major metrological parameters and reveals interaction with the object of measurement [24]. But definition of MI mentioned efficiency is partly subjective. Really the main function of any MI is receiving measurement information. It is naturally to consider the object of the measurement as source, and MI as a receiver of measurement information. This analog information is transmitted by the communication channel in which reduced to the input MI noises operate.

It is known that equivalent dispersion of the random input signals is determined as sum of different sources dispersions. During its definition it is necessary to take into account the sources of thermal and flicker noise. So we propose to determine the amount of MI received information M_{Ux} during voltage measurement of direct current on the basis of C.-E. Shannon theorem [25]:

$$M_x = Ct_x = t_x B \log_2\left(1+\frac{S_x}{N_n}\right) = t_x B \log_2\left(1+\frac{U_x^2}{D_{nU}}\right), \quad (1)$$

where t_x is the duration of measurement, $B=f_H-f_L$ is the bandwidth of the measuring channel, $S_x = \left(U_x^2/R_{in}\right)t_{mx}$ is the useful signal energy, $N_n = \left(U_n^2/R_{in}\right)t_{mx} = \left(D_n/R_{in}\right)t_{mx}$ is the energy of equivalent input noise, U_x is the measured voltage, R_{in} is the MI input resistance, U_n and $D_{nU} = D_{1U} + R_x D_{Iin} + 4kTR_x B$ are the voltage and equivalent input noise variance respectively, D_{n1U}, D_{Iin} are the variances of the voltage and the current equivalent noise respectively, k is the Boltzmann constant, T is the temperature of internal resistance of measured voltage source.

During electric current measurement I_x (with appropriate voltage drop on the R_{sh}) dispersion D_{nI} of equivalent noise is determined by the expression $D_{nI} = D_{1U} + R_{sh} D_{Iin} + 4kTR_{sh} B$, where R_{sh} is the shunt resistance. Analysis of the dispersions D_{nU} and D_{nI} of equivalent input noise at the measuring voltage or current reveals that they are formal similar and additive regarding active measurement values.

In the case of measurement of the electrical passive value resistance the expression $D_{nR} = D_{1U} + R_x\left(D_{Iin} + D_{Ics} + 4kTB\right)$ for equivalent noise dispersion contains multiplicative component besides additive one.

On the other hand, the main goal of the measurement process performing is receiving of measurement information numerical value of which is usually determined by the entropy (Shannon measure) or logarithmic measure of the uncertainty (Hartley measure). It is naturally to accept that output uncertainty is equal to width X_2-X_1 of MI measurement range, and uncertainty after measurement performing will be determined by the resolution error Δ_p of individual measurement results. Then on conditions of equiprobable dispersion laws of measured values and of their resolution error $\Delta_{r.e.}$, the amount of received information after measurement will be estimated by the relation [26]:

$$H_{mx} = \log\left(X_2 - X_1\right) - \log \Delta_{r.e.} = \log \frac{X_2 - X_1}{\Delta_{r.e.}}, \qquad (2)$$

where X_2-X_1 is the measurement bandwidth, $\Delta_{r.e.}$ is the resolution error of separate measurement results for given MI.

Quality factor K_x or efficiency of MI can be represented as the product of the two quantities of received measurement information:

$$K_x = M_x H_{mx} = t_x B \log\left(1 + \frac{X^2}{D_n}\right) \log \frac{X_2 - X_1}{\Delta_{r.e.}}, \qquad (3)$$

where $X=U_x$; $I_x R_{sh}$; $I_{sc} R_x$ are the input electrical signals while measuring voltage, current and resistance respectively.

From the analysis (3) we conclude that under all another similar conditions the amount of received measurement information with the help of MI is determined by the errors of measurement circuit which are caused by characteristics of the MI and object, measurement conditions, operator's qualification, duration etc. [11]. In practice under applying of polynomial model the expression for the resolution error can be submitted by the quadratic function [22-23]. At this moment necessary information on laws of probability distribution of elementary errors for finding the based on their composition the distribution resultant error is needed. By this distribution the confidence coefficient *k(P)*, can be determined correctly. Its value depends on confidence probability *P*. As result the resolution error estimation is difficult to assess. Besides with time *t* as a result of MI aging and wear its error alters (degrades). To ensure metrological reliability MI is produced with some technological reserve factor of which is equal to $k_{мн}$=0.4...0.8 concerning the acceptable error value [11, 21-24]. In most practical cases, the expression for the MI error $\Delta_{r.e.}(\tilde{o}, Đ, \vec{Q}, \vec{\xi}, k_n, t)$ in operation condition at moment *t* can be submitted as:

$$\begin{aligned} &\Delta_{r.e.}(x, Đ, \vec{Q}, \vec{\xi}, k_n, t) = \bar{\Delta}(x, \vec{Q}, \vec{\xi}, k_n, t) \pm \\ &\pm k(Đ, \vec{Q}, \vec{\xi}, t)\sigma(x, Đ, \vec{Q}, \vec{\xi}, k_n, t) = \Delta_{0\,r.e.}(P, \vec{Q}, \vec{\xi}, k_n, t) + \\ &+\delta_s(P, \vec{Q}, \vec{\xi}, k_n, t) \cdot \tilde{o} + \varepsilon(P, \vec{Q}, \vec{\xi}, k_n, t) \cdot \tilde{o}^2, \end{aligned} \qquad (4)$$

where $\Delta_0(P, \vec{Q}, \vec{\xi}, k_n, t) = \bar{\Delta}_0(\vec{Q}, \vec{\xi}, k_n, t) \pm k(P, \vec{Q}, \vec{\xi}, t)\sigma_0$ is the error additive component (EAC), $\delta_s(P, \vec{Q}, \vec{\xi}, k_n, t) = \bar{\delta}_s(\vec{Q}, \vec{\xi}, k_n, t) \pm k(P, \vec{Q}, \vec{\xi}, t)\sigma_\delta$ is the multiplicative error component, $\varepsilon(P, \vec{Q}, \vec{\xi}, k_n, t) = \bar{\varepsilon}(\vec{Q}, \vec{\xi}, k_n, t) \pm k(P, \vec{Q}, \vec{\xi}, k_n, t)\sigma_\varepsilon$ is the quadratic error component, $\vec{Q}$ is MI parameter vector, $\vec{\xi}$ is the vector of elementary errors, $k_н$ is MI nominal transfer factor, *P* is the confidence probability.

Random component of EAC is determined by MI noise components. Simultaneously it is necessary to take into account thermal noise and *1/f* noise. With *1/f* noise spectrum divergence in low-frequency limit a question about its stationary raises. However if MI low limit of frequency range is accepted the frequency f_{kl} of its calibration (determination of "zero" indexes) and upper limit is transmission frequency f_{hf}, then its *1/f* noise will be limited by frequency, and is stationary in first approximation which amplitudes (in the broad sense) are normally distributed [22-23].

Noise signal dispersions D_{nU} and D_{nI} reduced to MI input in the frequency range from $\omega_{kl}=2\pi f_{kl}$ to $\omega_{hf}=2\pi f_{hf}$ can be determined by means of Wiener-Khinchin theorem as [22-23, 27-28]:

$$D_n = \lim_{\tau \to 0} D_n(\tau) = A_{0\hat{a}}(f_{hf} - f_{kl}) + A_{fe} f_{fe} \ln \frac{f_{hf}}{f_{kl}}, \qquad (5)$$

where A_{0e}, A_{fe}, ω_{fe} are the spectral densities of thermal noise, *1/f* noise and circular frequency conjugation of noise equivalent densities respectively; $D_n=D_{nU}$; D_{nI}.

So in general case equivalent noise signal dispersions D_{nU} and D_{nI} reduced to MI input have additive and multiplicative components:

$$D_{nR} = D_{nU} + R_x \left[C_{0\hat{a}}(f_{hf} - f_{kl}) + C_{fe} f_{fe} \ln \frac{f_{hf}}{f_{kl}} \right], \qquad (6)$$

where C_{0e}, C_{fe}, f_{1fe} are the spectral densities of current thermal noise equivalent density, *1/f* noise and circular frequency conjugation of these noise respectively.

Except parameters A_{0e}, C_{0e}, A_{fe}, C_{fe} and f_{fe}, f_{1fe} which describe respectively thermal and *1/f* noise, dispersion also depends on MI parameters (its upper frequency f_{hf} of passband) and applied measurement algorithm including the considering the frequency f_{kl} of its calibration (zero indexes determination). At commensurate values A_{0e} and A_{fe} and dimension of f_{fe} at vicinity of hundreds hertz [17-18, 27-28], equivalent noise signal dispersion D_{nU} reduced to MI input increases with upper frequency f_{hf} of passband, and it hyperbolically decreases with increase of the frequency f_{kl} of the determination of MI zero indexes.

Excluding additive component under the same conditions the dispersion D_{nR} power of the equivalent noise signal reduced to MI input multiplicatively depends on measured resistance R_x value.

Correlation of (5) and (6) underline that system component of the error leads to shifted estimation of the measurement result uncertainty zone; moreover it also depends on change of ambient conditions and MI parameters. Among the variety of methods of errors automatic correction the preference should be given to the method of input channel inversion. Such MI contains compulsory polarity switch. Then measurement result N_x is determined as algebraic sum of results N_1, N_2 obtained at the opposite polarities of input signal. It enables to correct not only EAC, but also pair powers in the case of polynomial approximation of the MI transformation function [22-23]. The high degree of correction and simplicity of technical realization facilitates the implementation of input signal inversion in ΔΣ ADC microcircuits which inherent in quite satisfactory performance. F.i., the offset error specification of the ADC is ± 0.5 μV typical and the drift of these ADC's is specified as ±5 nV/°C typically, and in fact, it is practically immeasurable [22-23, 29].

6. Conclusions

1. Quality of measuring instruments is reasonable to evaluate by the product of two values: quantity of information received as a result of signals physical transformation throughout the measuring circuit, and quantity of information due to decrease in continuous quantity entropy after measurement. The proposed functional dependence connects to each other the energy and the information properties of elements of measuring circuit. In this case, the latter is regarded as the transmission channel of analog information from sources of active or passive electrical signals to the measuring tools through connection line with its own equivalent source of additive and multiplicative noise signals.

2. Amount of measurement data obtained from the measurement object through the analog transmission noisy-channel is proposed to estimate basing on Shannon–Hartley theorem. During the measurement of active electrical signals the equivalent noise reduced to input of measuring instrument, additively affects the gauging result. While measuring passive electrical signals the impact of equivalent noise is inherent in additive-multiplicative nature. Moreover, the bandwidth of the transmission channel of measurement data depends on the difference between the maximum frequency of this bandwidth and the frequency of adjusting transactions of bias voltage.

3. Taking into account both thermal noise and *1/f* noise, the expressions for the variance of equivalent noise during the measurement of active and passive electrical quantities are specified. Here the multiplicative component, caused by the influence of noise sources of whole measuring circuit, is taken into account.

4. To determine in these terms the quality of measuring instruments, it is suggested to apply an information factor as logarithmic measure of uncertainty, which value is practically determined only by measurement error. Auto adjustment of error additive component significantly enhances an information efficiency of measuring instruments.

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