Sensors & Transducers, Vol. 190, Issue 7, July 2015, pp. 81-85

Sensors & Transducers

http://www.sensorsportal.com

Metrological Array of Cyber-Physical Systems. Part 10. Foundations of Objective Qualimetry

[1] Svyatoslav YATSYSHYN, [1] Vasyl MOTALO, [1] Bohdan STADNYK and [2] Andriy MOTALO

[1] Lviv Polytechnic National University, 12 Bandera str., Lviv, 79013, Ukraine

[2] Gas production department Lvivgasmining, 27 Rubchaka str., Lviv, 79026, Ukraine

Tel.: +38-0322-37-50-89

E-mail: slav.yat@gmail.com

Received: 31 May 2015 /Accepted: 30 June 2015 /Published: 31 July 2015

Abstract: Contemporary trend of Cyber-Physical Systems evolution considers as promising line the metrology science development ability for estimation the quality of final or intermediate product. The reliability and perfection of smart and flexible operation of mentioned systems could be permanently improved if determination of critical characteristics would be performed correctly, and particular coordinated assessment would be non-correlatively fulfilled. Last is guaranteed at applying thermodynamic principles of coordinates' choice. *Copyright © 2015 IFSA Publishing, S. L.*

Keywords: Cyber-physical system, Objective qualimetry, Thermodynamics, Virtual product quality measure, Uncertainty of qualimetric measurements results.

1. Introduction and Current State of Problem

The existing cyber-physical system (further - CPS) development programs were suggested by scientists in automatics, software, networks and their security. However, their effective development is impossible without taking into account the metrological aspects of CPS designing, constructing and operating. Therefore current NIST program [1] focuses on involving metrological science to resolve some CPS-problems. For instance, the NIST program [2] focuses on four areas which are closely interrelated: material characterrization, real-time process control, process and product qualification, and systems integration. In the process and product qualification area, the program establishes foundations for equivalence-based qualification of materials, processes, and parts used in AM by developing novel test methods and protocols for round robin testing, as well as generating trusted data for sharing among the AM stakeholders.

2. Shortcomings

However, the continuous development of CPSs, designed schematically at least, by above-mentioned documents, comes up against a number of difficulties due to the following circumstances. Firstly, assign a priori that CPS creating [3] on the basis of industrial Internet opportunities envisages the free conjunction and matching of wares from different countries of different not fully estimated quality. As the current set of standards in different countries is insufficient to describe successfully the means and tools of modern scientific technology, it is constantly evolving and improving. Secondly, laboratories and leading research centers based on modern productive machinery are not able to be tested by virtue of their own complexity and problems of delivery to certified laboratories. Thirdly, unique and newly created machinery often requires self-verification and standardization of metrology facilities to ensure the quality work.

3. Goal of Work

Aim of this paper is the Methodological principles development of establishing the contemporary objective type of qualimetric measurements as the new direction of Cyber-Physical Systems and/or their products quality evaluation.

4. Development of Qualimetry in Additive Manufacturing and Related Fields

The basis of any measurement is comparison of the measured value with a reference or standard that retains and reproduces a physical quantity of the certain dimension. Specificity of qualimetric measurement is the absence of specific physical measures of the quality of particular products. Available basic product samples not always correspond to the metrological requirements that are applied to measures. Therefore not always possible methodologically to compare the studied products with the basic sample that, in fact, constitutes the main problem of these measurements implementation.

4.1. Conceptual Principles

To ensure methodological implementation of quailmetric measurement procedures is suggested virtual measure of product quality, which is a theoretical analogue of corresponding physical measure, i.e. the reference sample of the studied product [4]. To construct the *product quality virtual measure* [5] is applied the basic provisions of virtual instrumentation technology as one of modern information technologies. Its essence lies in a computer program that simulates real physical instrumentation, measuring systems and control, as also the set theory of mathematics. Thus, virtual measure of product quality corresponds to mathematical expressed and software backed real physical measure.

On the other hand, the product quality is defined by a set of the different origin's properties. So, virtual measure of product quality is a plurality of some arbitrary objects, united by certain properties common for these units. Such objects in Qualimetry are individual absolute P_i and relative K_i indicators of products quality ($i = 1, 2, 3, ..., k$, where k is the number of individual indicators, which equals to number of properties p_i). Proceeding from this analysis, synthesis of virtual measure of product quality is carried out on dot sets theory basis in n-dimensional Euclidean space (n is the number of coordinates), in which are made the product quality assessing. That is due to different physical nature and various dimensions of individual absolute indicators of product quality P_i. The latter are points on the corresponding coordinate axes of multidimensional space. Hereby, scales on certain i-coordinate axes are different and determined by weight coefficients m_i of appropriate individual quality indicators P_i.

4.2. Methodology of Qualimetric Measurements Realization in Mechanical Manufacture

At resolving theoretical and practical problems of qualimetric measurement in quality evaluation of construction materials we have developed a comprehensive methodology for determining quality by considering properties and internal structure impact on decisive indicator of the quality, namely by using the measurement uncertainties of gained results.

For this purpose primarily there were analyzed characteristics of construction materials quality and was chosen quality evaluation method; then was established a decisive indicator of quality for their strength evaluation considering the relationship between this indicator and structure-sensitive properties; ultimately was studied this indicator measurement method taking into account the substance internal structure as well as and the method of assessment of aforementioned indicator measurement accuracy.

In examination were also taken into account that most important characteristics of constructional materials include elastic properties in particular modulus of elasticity. That is due to the next. Modulus is related with energy of crystal lattice and is a measure of atomic bonds so can be applied in materials research particular in study of substance structure, phase transformations and more. In addition, the elastic modulus is used in mechanics of solids at designing the details and units of various machines as makes it possible to predict the material response on applied load.

In materials science an ultrasonic pulse method for measuring mechanical properties is widespread; it provides the highest exactness. The method is based on the dependence of longitudinal elastic ultrasonic waves (UW) speed υ in tested material on its modulus of elasticity and density:

$$E = \rho \upsilon^2, Pa, \quad (1)$$

where ρ is the material density, kg/m^3; υ is the measured UW velocity in a sample, m/s. The measurement error consists of two constituents: instrumental one $\delta_{E,instr.}$ and another methodical one $\delta_{E,met.}$, or:

$$\delta_E = \delta_{E,instr.} + \delta_{E,met.}, \quad (2)$$

and $\delta_{E,met.}$ can be equal to few percent, that is much greater than $\delta_{E,instr.}$ making the main contribution to the value of total error δ_E of the mechanical properties measurement.

Thus, we have developed a technique of correcting until excluding the methodical constituent of measurement error while ultrasound method application. Behind it, simultaneously to measuring the velocity of UWs it should be measured one of following structure-sensitive characteristics of sample's material. For instance, these can be considered specific conductivity γ for conductive materials, relative dielectric permeability ε for dielectrics or relative magnetic permeability μ for ferromagnets. The resulting corrected value of elasticity modulus of studied pattern is determined taking into account these additionally measured parameters. The appropriate equations for calculating the adjusted modulus values E_M of different construction materials EM as a primary indicator of quality for the developed technique are presented in Table 1.

Table 1. Corrected values of elastic modulus of materials.

No.	Kind of sample substance	Equation of corrected values of elastic modulus E_M, Pa
1.	Conductive materials	$E_M = \rho_o \upsilon^2 \frac{\gamma_o}{\gamma},$
2.	Dielectrics	$E_M = \rho_o \upsilon^2 \frac{\varepsilon_o}{\varepsilon}$
3.	Ferromagnets	$E_M = \rho_o \upsilon^2 \frac{\mu_o}{\mu}$

Remark 1. Here ρ_o is the theoretical density of defect-free material, kg/m^3; γ is the real electrical conductivity of the sample substance with structure defectiveness, 1/(Ω·m); γ_0 is the theoretical electric conductivity of defect-free material, 1/(Ω·m); ε is the real relative dielectric permeability of sample substance with structure defectiveness; ε_o is the theoretical relative dielectric permeability of defect-free material, μ is the real relative permeability of the sample with defectiveness; μ_o is the theoretical relative permeability of defect-free material.

Evaluation for measurement accuracy of corrected values of construction materials elasticity modulus was carried out by means of assessing the measurements uncertainty, i.e. values of modulus E_M, of studied samples. For this purpose technique of defining uncertainty $u(E_M)$ of elastic modulus E_M received value was developed. Its peculiarities consist of the following considerations. First, modulus measurement result E_M in the case of measurements with multiple observations on condition the normal distribution of these observations $E_{M,i}$, are calculated as mean sampling value $\overline{E}_M$, obtained from individual modulus measurements $E_{M,i}$, [Pa] (i =1, 2, 3, …, n, here n is the number of individual measurements).

The latter are determined by the formulas given in Table 1 dependently on the kind of studied sample substance:

$$E_M = \overline{E}_M = \frac{1}{n}\sum_{i=1}^{n} E_{M,i}, Pa \quad (3)$$

Second definition of elastic modulus values $E_{M,i}$, of each of n measurement results, as can be seen from the formulas (Table 1), depending on the type of studied samples, are indirect measurements. Third, as for sustainable measuring conditions of experiment obtainned results of individual measurements of modulus E_M, are equally accurate, then the standard uncertainty of type **B** of elasticity modulus E_M measurement result is found on the basis of uncertainty analysis of only one measurement result $E_{M,i}$ from obtained n results.

Thus, the combined standard uncertainty $u_c(E_M)$ of elastic modulus measurement result E_M of construction materials by ultrasound pulsed method consists of standard uncertainty of type **A** $u_A(E_M)$ that is determined statistically by processing a sequence of n observations $E_{M,i}$ of studied material:

$$u_A(E_M) = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}\left(E_{M,i} - \overline{E}_M\right)^2}, \quad (4)$$

and combined standard uncertainty of type **B** $u_{cB}(E_M)$, Pa, which is defined by processing the results of indirect measurements. Determination of combined standard uncertainty of type **B** $u_{cB}(E_{M,i})$, Pa, of elastic modulus measurement result $E_{M,i}$, Pa of i^{th} observation is carried out by analyzing the general relation:

$$E_{M,i} = \rho_o \upsilon_i^2 \frac{\chi_o}{\chi_i}, Pa, \quad (5)$$

where χ_o i χ_i are the generalized designations of studied material's structurally-sensitive properties.

They are applied to correct methodical error of modulus measurement. Similarly are used specific conductivity values γ_o, γ_i while studying the electrically conductive materials, and relative dielectric permeability ε_o. ε_i in the case of dielectric materials research. The same concerns relative magnetic permeability μ_o i μ_i at ferromagnetics research.

Combined standard uncertainty u_c (E_M) of investigated material modulus E_M measurement result is defined as the square root of sum of the squares of predetermined standard uncertainty of type **A** $u_A(E_M)$ and the combined standard uncertainty of type **B** $u_{cB}(E_{M,i})$:

$$u_c\left(E_M\right) = \sqrt{u_A^2\left(E_M\right) + u_{cB}^2\left(E_{M,i}\right)} \quad (6)$$

The uncertainties' budget of studied material modulus is given in Table 2.

Table 2. Uncertainties' budget of studied material elastic modulus E_M.

Input value x_j	**Standard uncertainty** $u(x_j)$	**Evaluation type, distribu-tion law**	**Coefficient of sensitivity** $C_j = \partial f / \partial x_j$	**Product of** $\lvert C_j \rvert \cdot u(x_j)$
ρ_o, kg/m^3	$u_B(\rho_o) = \frac{q_{\hat{e}\hat{a},\rho_o}}{2\sqrt{3}}$, kg/m^3	Type **B**, uniform	$C_{\rho_o} = \upsilon_i^2 \frac{\chi_o}{\chi_i}$, m^2/s^2	$C_{\rho_o} \cdot u_B(\rho_o)$, Pa
υ_i, m/s	$u_{cB}(\upsilon_i)$, m/s	Combined, normal	$C_{\upsilon_i} = 2\upsilon_i \rho_o \frac{\chi_o}{\chi_i}$, kg/(m^2·s)	$C_{\upsilon_i} \cdot u_{cB}(\upsilon_i)$, Pa
χ_o, 1_χ	$u_B(\chi_o) = \frac{q_{\hat{e}\hat{a},\chi_o}}{2\sqrt{3}}$, 1_χ	Type **B**, uniform	$C_{\chi_o} = \frac{\rho_o \upsilon_i^2}{\chi_i}$, kg/(m·s^2·$1_\chi$)	$C_{\chi_o} \cdot u_B(\chi_o)$, Pa
χ_i, 1_χ	$u_{cB}(\chi_i)$, 1_χ	Combined, normal	$C_{\chi_i} = -\frac{\rho_o \upsilon_i^2 \chi_o}{\chi_i^2}$, kg/(m·s^2·$1_\chi$)	$C_{\chi_i} \cdot u_{cB}(\chi_i)$, Pa
Output value	Evaluation type, distribution law	Combined standard uncertainty		
$E_{M,i}$, Pa	Combined, normal law	$u_{cB}\left(E_{M,з}\right) = \sqrt{C_{\rho_o}^2 u_B^2(\rho_o) + C_{\upsilon_i}^2 u_{cB}^2(\upsilon_i) + C_{\chi_o}^2 u_B^2(\chi_o) + C_{\chi_i}^2 u_{cB}^2(\chi_i)}$, Pa		

5. Objective Qualimetry on the Basis of Thermodynamics

Assessment of products quality is a complex multifactorial problem, within which is difficult to evaluate the role and relative weight of each factor, as well as to expressed in physical units the objective numerical value of it or to validate this factor, and finally to determine certain characteristics. At best, the result is expressed as the number reasonably combining all these influence factors. That is a **Subjective Qualimetry**. It is exploited while comparing the similar products of the same destination from different manufacturers. However, no one can prove conclusively the correctness of the choice of those or other factors that affect the assessment.

From the metrological point of view, no one can guarantee absence of correlation for separate factors among themselves that negative influence on the obtained results. As this comparison becomes in a certain degree subjective, it would be performed only for products of very similar appointment, e.g. vehicles of the same sector, power, etc. In terms of metrological-qualimetric approach this is the result of only researcher's subjective approach concerning correct choice of coordinates (major characteristics, by which the studied object is estimated). Indeed, when selected coordinates are somehow associated (in metrological sense correlated), then correlativity is not considered in the obtained results at least by correlation coefficients and final results become unreliable. Mutual correlation of certain parameters is often explicit, often evident, but hardly argued. For instance, returning to cars' estimation, we can note that quality of outer covering that forms such qualitative parameter as the appearance car, is however involved in fuel economy. So, the mentioned parameters could consider to be significantly correlated with the high correlation coefficient.

Previously on the basis of studying factors influencing the performance of thermoelectric sensors, to evaluate their metrological quality we suggested [6] to carry out methodologically correct selection of uncorrelated factors. The basis for this implementation was taken similar to adopted in thermodynamics [7]. The latter ensures correctness of choice the determining factors – characteristics – of being evaluated product or process as a set of unrelated variables (measurands in metrology) denominated as thermodynamic forces and flows. This thermodynamics approach is able to provide an **Objective Qualimetry** to create multidimensional space with guaranteed independent and uncorrelated coordinates. Currently in phenomenological thermodynamics are known [7] 6 independent degrees of freedom. They cover almost all physical phenomena eligible to describe the characteristics of arbitrary objects, conjugated by certain properties for estimating goals. For instance, in [8] we disclosed the path how to tie aforementioned Young's modulus through superficial freedom degree of the basic equation of thermodynamics with thermo-EMF drift of thermoelectric thermometer manufactured from cermet materials. Obtained results fully coincide with given above in Tables 1 and 2 expressions for the modulus of elasticity.

Should be noted that on the basis of empirical experience Qualimetry works with linear algebraic expression of type:

$$U = aX + bY + ... + kZ, \quad (7)$$

where *a, b, c* are the coefficients; *X, Y, Z* are the studied properties, or coordinated which number is defined by researcher. Since operating in *n*-dimensional Euclidean space, the proper establishing the size of vector, which module *P* is determined from the following expression:

$$P^2 = aX^2 + bY^2 + ... + kZ^2, \quad (8)$$

can serve as integer giving the assessment, especially when coordinates are specified independent by involving thermodynamic approach. In thermodynamics expression of type aX^2, where X is thermodynamic force concerning the certain freedom degree, corresponds to the dimension of energy. Therefore at correct choice of studied properties in (8) the received result is equivalent to P^2 under that dimension.

Thus, proposed approach with proper choice of coordinates describing the relevant properties of studied object leads to absolutely correct its qualimetric assessment, which coincides with the thermodynamic evaluation on the energetic basis.

Remark 2. In thermodynamics due to equations of state it appears to choose any parameters of the system as independent variables. At a certain choice of independent variables there are always functions of the system that are successful for studying various processes. These thermodynamic functions are named as thermodynamic potentials or characteristic functions if they satisfy the following requirements:

a) They have to be additive and unique functions of the system state;

b) For a particular set of physical variables their derivatives are inherent in simple and clear physical meaning;

c) Under certain conditions the thermodynamic function in equilibrium is characterized by extremum.

6. Conclusions

For comprehensive quality assessment of complex products produced by Cyber-Physical Systems and comparing between similar products of the same destination from different manufacturers it could be offered a newly established field of metrology that is specified as Objective Qualimetry. In contrast to traditional Subjective Qualimetry the latter is able to realize the selection of metrologically uncorrelated row of determining characteristics of these products and, thus, to identify products of higher quality. Determination of critical characteristics, especially those that do not correlate with a number of other characteristics, is crucial for paying the maximum attention to metrological assurance as well as to validation of these particular characteristics for Cyber-Physical System specific type or for its final product, and can be achieved only on the basis of thermodynamically justified involvement. As result, the reliability and perfection of smart and flexible operation of mentioned systems could be permanently improved.

Acknowledgement

The scientific results, presented in this article, were obtained in the frame of research project number 0115U000446, 01.01.2015 - 31.12.2017, financially supported by the Ministry of Education and Science of Ukraine.

References

[1]. National Technical Information Service (NIST), FY 2014, Budget Submission to Congress, 2014.

[2]. ASTM International, Technical Committee F42, Additive Manufacturing Technologies, http://www.astm.org/ COMMIT/ COMMITTEE/ F42.htm

[3]. Project of the Future: Industry 4.0 (http://www.bmbf. de/en/19955.php).

[4]. B. Stadnyk, V. Motalo, Evaluation of Qualimetrical Measurements Quality Based on the Uncertainty Concept, *Pomiary. Automatyka. Kontrola*, Warszawa, Vol. 59, Issue 9, 2013, pp. 950-953.

[5]. P. E. Green, J. Frank, Jr. Carmone, Sc. M. Smith, Multidimensional Scaling: Concepts and Applications, *Allyn & Bacon*, Boston, 1989.

[6]. B. Stadnyk, S. Yatsyshyn, Accuracy and metrological reliability enhancing of thermoelectric transducers, *Sensors and Transducers*, Vol. 123, Issue 12, December 2010, pp. 69-75.

[7]. P. Glansdorf, I. Prigogine, Thermodynamic theory of structure, stability and fluctuations, *Wiley-Interscience,* New York, N. Y., 1971.

[8]. S. Yatsyshyn, B. Stadnyk, Ya. Lutsyk, Impact of porosity on the changes of thermo-EMF of thermometric materials, *Bulletin of National University "Lviv Polytechnic", Automation, Measurement and Control*, Issue 530, 2005, pp. 22-28 (in Ukrainian).