UDC 006.91:681.2-5:62-5

Ensuring uniformity of measurements in the European Metrology Cloud

T. Bubela, V. Yatsuk, M. Mykyjchuk, O. Kochan, Yu. Yatsuk

Lviv Polytechnic National University, S. Bandera Str., 12, 79013, Lviv, Ukraine
vasyl.o.yatsuk@lpnu.ua

Abstract

The main requirements for the calibration of measuring channels of distributed measuring instruments at the operation site are described. When preparing for calibration, the use of portable discharge working measurement standards, which consist of a reference voltage source and a divider, is substantiated. The proposed structure of the device for calibration is based on a divider of single-nominal resistors and corresponding algorithms for processing the conversion results. The feasibility of using a divider in which the resistors are closed in a ring is substantiated. To ensure the invariance to residual parameters of switching elements when implementing several evenly spaced calibration points in the conversion range, a potential-current switching of both the input reference voltage and the output converted voltage is proposed. In addition, a method to correct the equivalent additive error component of the entire measuring channel during its calibration is proposed. The expediency of the studied measuring channels to obtain intermediate conversion results is shown. An algorithm and method of processing intermediate conversion results to obtain code values at all calibration points are proposed. To process these results, it is advisable to apply an additional software in the European Metrology Cloud. It is shown that the calibration error of the measuring channels at the operation site is determined by the error of the reference voltage source.

Keywords: measuring channels; distributed systems; automatic error correction; on-site calibration.

Received: 12.02.2024 Edited: 11.03.2024 Approved for publication: 14.03.2024

Introduction

In today’s world, the global digitization of all aspects of the economy becomes its accelerator and a condition for ensuring the product quality and competitiveness [1, 2]. For many organizations, the problem of transforming complex production processes into digital equivalents is a complex problem. In technological processes of modern “Industry 4.0”, distributed measuring systems (DMS), in particular cyber-physical systems (CFS), are widely implemented. Such systems collect measurement information about various parameters of many spatially dispersed objects. In view of this, the traditional calibration methods for measuring channels (MC) of such systems in special calibration (measuring) laboratories become practically unacceptable. In addition to high labour and cost, generally accepted calibration methods usually do not take into account the uninformative effects of input and output signal lines and channels for transmitting measurement information. The concept of the “factory of the future”, which is built on the basis of networks of industrial sensors, is also being actively developed, therefore the development of basic metrological principles for its implementation is urgent. The tools of the Internet of Things (IoT) also need to ensure the quality of received data. Therefore, the integration of fundamental principles of the traceability and measurement uncertainty evaluation of the IoT data is an area of active research.

The combination into a harmonious overall digital process can be demonstrated on the example of the digital transformation of metrological services of the German National Metrological Institute (PTB) with its subsequent transformation into a compatible digital infrastructure of quality [3].

Analysis of recent research and publications

Key issues and the potential role of metrology in the era of digital technologies are actively considered. In particular, metrological principles of trust in data and algorithms, CFS, FAIR data and metrology, as well as the role of metrology in digital transformation in the quality infrastructure are of great attention [4, 5]. For example, in [6, 7], basic metrological

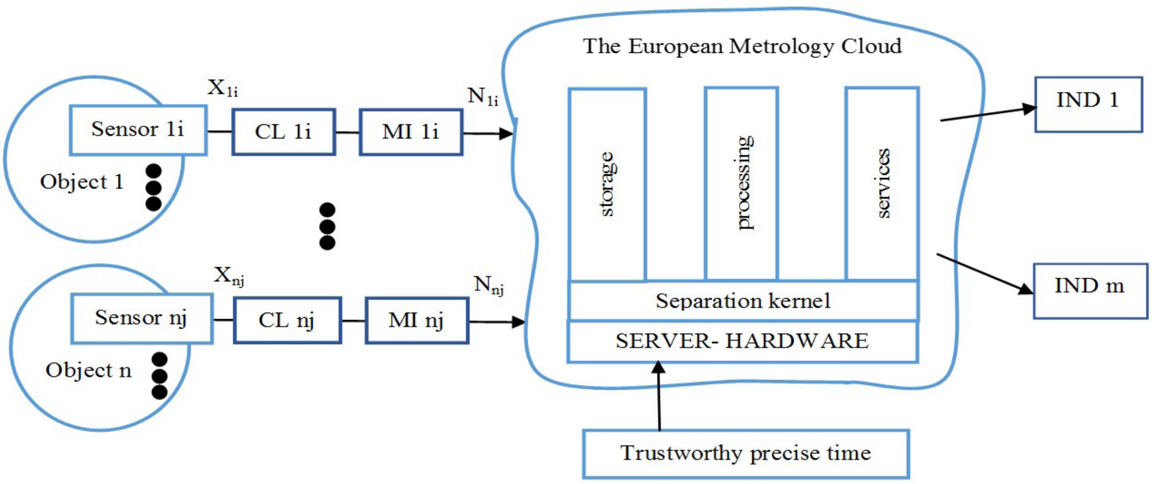

Fig. 1. Concept structure of the European Metrology Cloud as a distributed measurement system

principles regarding calibration, measurement uncertainty, and traceability for obtaining comparable and reproducible measurement results in the IoT are studied. To ensure the reliability of metrological data, digital calibration certificates have been developed that enable electronic storage, an authenticated, encrypted and signed transfer procedure and a unified interpretation of calibration results [8]. However, for large metrology institutions, such certificates also have problems related to the huge amount of information provided, reports with complex data and the security nature of calibration reports [9]. To ensure the quantitative determination of data quality in the IoT tools, it is proposed to set their error limits based on distributed ledger technology.

Digital transformation fundamentally changes the main foundations of the quality infrastructure – metrology, standardization, accreditation, conformity assessment and market surveillance. Therefore, a strategy of digital transformation has been prepared and implemented in the EU to build a quality digital infrastructure "European Metrology Cloud" (EMC) (Fig. 1) [10]. This strategy is designed to support the evaluation of processes concerning compliance and market surveillance, development of reference architectures as well as the new technology and data-driven services for this infrastructure.

Today, EMC has reached the stage of practical completion of the development of the basic set of functions. In the future, the main focus will no longer be on architecture development, but on the creation of digital representations ("smart contracts") for more processes in legislative metrology, and on the integration of more stakeholders with their databases. At the same time, the PTB group continues work on compatibility with future GAIA-X standards and new generations of smart remote control systems [11].

One of the greatest advantages of the EMC is a successful attempt to digitize the processes of metrological activity and build a digital quality infrastructure on this basis. The lack of practical recommendations on the calibration of the measuring channels of the EMC at the operation site should be considered among the shortcomings of the EMC.

It was noted that self-calibrating RC using portable small-sized measurement standards built on fundamental natural constants can be the most appropriate solution for ensuring the uniformity of measurements in the RDS under operating conditions [12]. However, at the same time, the remote prospect of practical implementation of such standards at an affordable price is indicated.

The aim of this paper is to develop the basis for the development of portable devices for calibration of measuring channels of distributed systems at the operation site.

To achieve this goal, it is proposed to use portable code-controlled measures (PCCM), which are pre-calibrated in special laboratories (Fig. 2) [13, 14]. During the operation of the DMS, it is necessary to ensure the practical invariance of the calibration results from the influence of non-informative parameters, especially changes in the PCCM transformation function. In addition, according to the recommendations of regulatory documents, calibration of MC can be carried out only in several points evenly distributed in the conversion range [15–17]. Therefore, from a practical point of view, there is no need to use multi-bit code-controlled dividers (CCDs) and CCDs designed to reproduce several points [15, 17]. It is suggested to use resistive CCDs, since capacitive ones can be implemented only on direct currents [18].

Note that in the European Metrology Cloud, a separate CMD hardware and software unit should be allocated. Here, controlled measures CM1i,..., CMnj would be placed at the inputs of measuring channels, which receive remotely transmitted codes from the CMD block. Then the calibration procedure of a certain measurement channel would involve obtaining (from the controlled measures CM1i,..., CMnj) a certain sequence of codes from the CMD block. Each code received by the controlled measures is

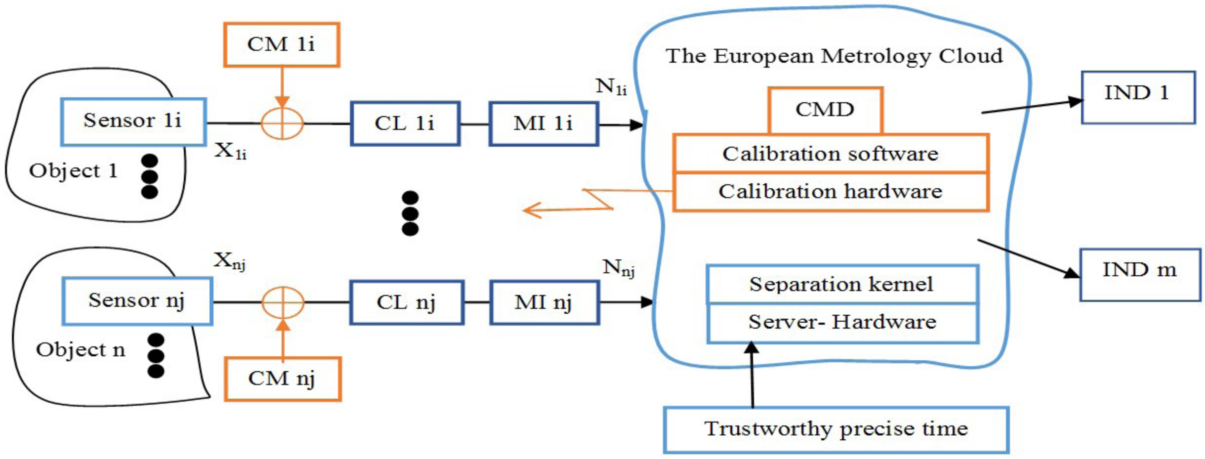

Fig. 2. Structural implementation of the calibration of measuring channels of distributed systems at the operation site

converted into a precise and stable analogue value; further, it is transformed into an input code for the CMD block through a measuring channel. Depending the on voltage of the calibrated point, the input codes are perceived and processed according to the developed algorithm.

During calibration, the additive component error (AEC) reduced to the MC input will be added to the equivalent AEC of the PCCM measure. It is advisable to automatically adjust this equivalent AEC applying a calibrated MC. In addition, it is practically very convenient to use the "digital" capabilities of the EMC in relation to the wireless addressable transmission of control codes to the MC of the PCCM located at the inputs. It is also convenient to work out the results of transformations, find and save corrections or calibration coefficients for each of the tested points.

It is known that during the switching of certain groups of single-rated resistors and processing of corresponding codes of the results of intermediate transformations, the division coefficient of such a CCD will not depend on their instrumental errors [15–17]. This creates the prerequisites for the construction of the PCCM for the calibration of measuring channels of the DMS at their operation sites (Fig. 3). To ensure invariance to resistor errors, they must all be turned on during the implementation of all coefficient values.

This approach is used to determine the nonlinearity error of the ADC. The analysis shows the suitability of its implementation even with small ADC nonlinearity errors [17]. One of its biggest disadvantages of the analysed CCDs is the technical difficulties when implementing division coefficients greater than 0.5.

A resistive divider R_1, ..., R_n, closed in a ring, is the basis of the structure of the controlled measures during the software-hardware implementation of several points evenly located along the transformation range (Fig. 3).

It is based on a resistive divider R_1, ..., R_n, closed in a ring. The structure provides the possibility of invariant connection to the certain group of divider resistors by potential-current switching of the outputs of the reference voltage source (RVS) (two buffer elements and a pair of potential switches SW1, SW4 and current switches SW2, SW3). Voltage drops on the certain groups of resistors can be connected to the inputs of measuring channels by a pair of switches SW5, SW6 and a differential amplifier DA.

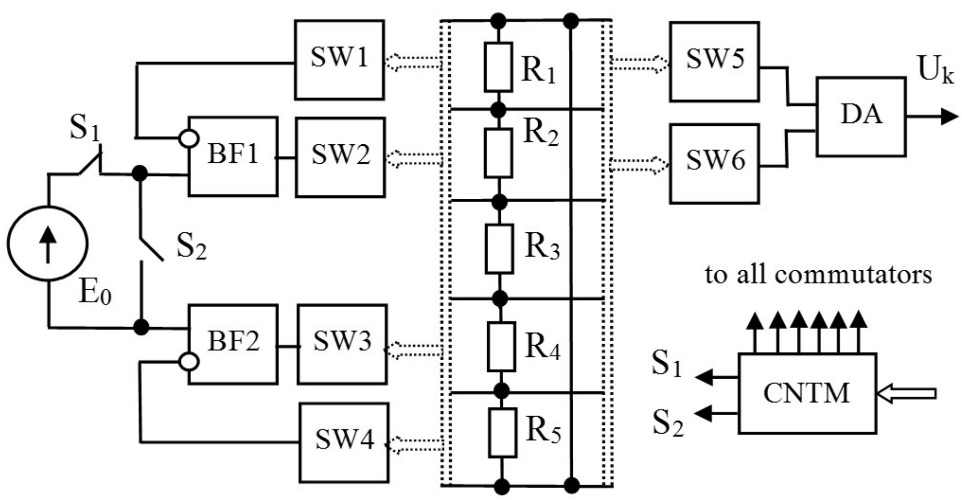

Fig. 3. The structure of the controlled measures for implementation of several ones

Table 1

Mathematical models of some signals during calibration

Point number	MC parameter	Mathematical models
1	Input voltage U_{1in}	$U_{1in}=U_{\Delta i}=\Delta_{SWi}+\Delta_{AD}$
	Conversion $N_{\Delta i}$ code	$N_{\Delta i}=k_{AD}\,U_{\Delta i}$
2	Input voltage U_{2Ri}	$U_{2Ri}=E_0\dfrac{R_i}{R_\Sigma-R_1}+U_{\Delta i}$, where $R_\Sigma=\sum\limits_{i=1}^{5}R_i=\overline{R}$; $R_i=\overline{R}(1+\delta_{Ri})$; $\delta_{Ri}=\dfrac{R_i-\overline{R}}{\overline{R}}$; $\sum\limits_{i=1}^{5}\delta_{\bar{R}i}=0$; i=1,…,5
	Conversion $N_{\Delta i}$ code $N_{2R0i}=k_{AD}U_{2Ri}-N_{\Delta i}$	$N_{2R0i}=k_{AD}\left(E_0\dfrac{R_i}{R_\Sigma-R_1}\right)$
	Calibration code	$N_{025}=0.25\sum\limits_{i=2}^{5}N_{2R0i}=0.25\,k_{AD}\,E_0$
3	Conversion $N_{\Delta i}$ code U_{3Ri}	$U_{3R1}=E_0\dfrac{R_2+R_3}{R_\Sigma-R_1}+U_{\Delta i}$; $U_{3R2}=E_0\dfrac{R_4+R_5}{R_\Sigma-R_1}+U_{\Delta i}$, where i=1.2
	Conversion code $N_{3R0i}=k_{AD}U_{3Ri}-N_{\Delta i}$	$N_{3R01}=k_{AD}\left(E_0\dfrac{R_2+R_3}{R_\Sigma-R_1}\right)$; $N_{3R02}=k_{AD}\left(E_0\dfrac{R_4+R_5}{R_\Sigma-R_1}\right)$
	Calibration code	$N_{050}=0.50(N_{3R01}+N_{3R02})=0.50\,k_{AD}\,E_0$
4	Input voltage U_{4Ri}	$U_{4Ri}=E_0\left(1-\dfrac{R_i}{R_\Sigma-R_i}\right)+U_{\Delta i}$
	Conversion code $N_{4R0i}=k_{AD}U_{4Ri}-N_{\Delta i}$	$N_{4R0i}=k_{AD}\,E_0\left(1-\dfrac{R_i}{R_\Sigma-R_i}\right)=k_{AD}\,E_0\left(1-0.25\dfrac{1+\delta_i}{1-1.25\,\delta_i}\right)$; $N_{4R0i}\cong k_{AD}\,E_0(1+2.25\,\delta_i+0.625\delta_i^2)$
	Calibration code	$N_{075}=0.2\sum\limits_{i=1}^{5}N_{4R0i}=0.25\,k_{AD}\,E_0\left(1+0.125\sum\limits_{i=1}^{5}\delta_i^2\right)$
5	Input voltage U_{5in}	$U_{5in}=E_0+U_{\Delta i}$
	Calibration code	$N_{100}=k_{AD}E_0$

Code packets from the CMD unit are received by the CNTM controller of the considered measures.

For calibration, it is advisable to choose the following control points 0; 0.25; 0.50; 0.75; 1.00. Before reproducing the calibration voltages at each of the indicated points, the automatic adjustment of the MC is carried out using the method of sample signals by disconnecting the input of the RVS and connecting the two inputs of the buffers together. For any configuration of the structure of the measure, a signal is formed in it, the value of which is proportional to the equivalent AEC: $N_{\Delta i}=k_{AD}(\Delta_{SWi}+\Delta_{AD})$, where Δ_{SWi}, Δ_{AD} – respectively, AEC caused by the influence of the residual parameters of switches SW1,..., SW6, S1, S2 is reduced to the entrance of the AEC of MC. This AEC value will then be subtracted from the current transform code values for each of the structure configurations.

In the second and third calibration points, the voltage E_0 RVS is applied to the first R_1 resistor, and the code is converted to the voltage inheritances, respectively, on each of the resistors R_2, ..., R_5, or groups of resistors R_1+R_2 and R_3+R_4. During the implementation of the fourth calibration point, the voltage E_0 RVS is applied to each R_1, ..., R_5 resistors in turn, and the algebraic sum of the voltage drops on the included R_i, and neighbouring R_{i+1} resistors is converted into the code. At the fifth calibration point, the E_0 RVS voltage is applied to the PCCM output. Table 1 shows mathematical models during calibration at all points.

If to choose relatively accurate resistors for the implementation of a resistive divider with a maximum error value under variable operating conditions $(\delta_{Ri})_{max} \leqslant \pm 5\times 10^{-3}$, then the estimate of the quadratic term will not exceed $\pm 2\times 10^{-5}$. This makes it possible to implement portable code-controlled voltage measures for the calibration of measuring channels of distribu-ted measuring systems at the operation site.

Discussion and outlooks

Under the condition of AEC automatic adjustment, the error of setting the calibration voltages is determined only by the RVS error. The result of calibration under the operating conditions does not depend on the values of divider resistors. The precision voltage sources have produced for a long time, for example, the LTZ1000 series with an extremely small voltage temperature coefficient of 0.05 ppm/°C. This means that even with the very wide operating temperature range –40... to +125 °C, their reference voltage value does not change more than 5 ppm, or 0.0005% [18]. So, the proposed device for the calibration provides the highest accuracy under these conditions. Considering the sufficient stability of the LTZ1000 source, its voltage value can change no more than ±1 ppm/month, ±120 ppm/120 months, and ±0.012% during ten years of operation. If it is necessary to obtain lower values of the reference voltages, other types of microcircuits should be used, for example presented in [18], but with slightly worse metrological parameters.

It should be noted that the circuit solutions of the studied device are close to the circuit technology of precision and stable DACs. This provides a fundamental opportunity to implement such a block as a separate microcircuit.

Conclusions

The studied device is designed as a stand-alone unit for the calibration of measuring channels of distributed systems under operating conditions. If short-term stability is ensured (during the calibration time of the measuring channels at the operation site), its metrological properties are determined only by the parameters of the reference voltage source.

Due to a complex of satisfactory metrological characteristics, the proposed device can be used as a portable working measurement standard for calibrations/verification of measuring channels of distributed systems at the operation site.

The considered device can be manufactured as an integrated microcircuit.

Єдність вимірювань у європейській метрологічній хмарі

Т.З. Бубела, В.О. Яцук, М.М. Микийчук, О.В. Кочан, Ю.В. Яцук

Національний університет "Львівська політехніка", вул. С. Бандери, 12, 79013, Львів, Україна
vasyl.o.yatsuk@lpnu.ua

Анотація

Описано основні вимоги до калібрування вимірювальних каналів розосереджених засобів вимірювань на місці експлуатації. Під час підготовки до калібрування обгрунтовано використання переносних розрядних робочих еталонів, які складаються з джерела опорної напруги та подільника. Запропоновано структуру пристрою для калібрування з використанням подільника з однономінальних резисторів та відповідні алгоритми опрацювання результатів перетворення. Обгрунтовано доцільність застосування подільника, в якому резистори замкнені в кільце. Для забезпечення інваріантності до залишкових параметрів комутаційних елементів під час реалізації декількох рівномірно розташованих калібрувальних точок у діапазоні перетворення запропоновано потенціально-струмове перемикання як вхідної опорної напруги, так і вихідної перетворюваної напруги. Показано доцільність використання досліджуваних вимірювальних каналів для отримання проміжних результатів перетворення. Запропоновано алгоритм і методику опрацювання проміжних результатів перетворення для отримання значень кодів в усіх калібрувальних точках. Обробку цих результатів доцільно проводити з допомогою додаткового програмного забезпечення в європейській метрологічній хмарі. Відзначено також доцільність бездротового передавання кодів калібрувальних точок, що суттєво спростить практичну реалізацію процедури калібрування вимірювальних каналів у європейській метрологічній хмарі.

Показано, що похибка калібрування вимірювальних каналів на місці експлуатації визначатиметься практично тільки похибкою джерела опорної напруги. Отримані експериментальні результати можуть бути використані для оформлення цифрових сертифікатів калібрування.

Ключові слова: вимірювальні канали; розподілені системи; автоматичне коригування похибок; калібрування на місці експлуатації.

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