MEASURING SYSTEMS

FEATURES OF TRANSFERRING SIZE OF LENGTH UNIT FROM WORKING STANDARD TO MEASURING DEVICE

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Abstract. The paper examines the characteristics of accuracy when transferring the size of a unit of length from a standard to an industrial measuring device. Based on the processing of the calibration results, the peculiarities of using different transfer schemes within the limits of the current regulatory document were considered. The problems that arise are studied. To ensure an effective scheme of transfer and unity of measurements, the expediency of application of the method of RMS deviations in the analysis of the obtained measurement results is shown.

Key words: Unity of measurements, measuring mean, standard, root mean square deviation, calibration

1. Introduction and statement of the problem

Organization of ensuring the transfer of the size of a unit of length can be considered an urgent task today. This is realized in various sections of the State Verification Scheme of Length Measuring Instruments [1], where the conception of the transfer of unit size is described, namely from working standards to industrial measuring means (MMs). At the same time, it is considered important to study the built-in standards of physical values [2], as well as so-called "intrinsic" [3] standards. The latter are often built based on quantum effects, both for the generation of a highly stable reference signal [4] and for the direct use of physical constants [5] to ensure the value of a measure of a physical quantity. Here, in addition to the unit of length, the unit of electric voltage [6], expressed through the value of frequency, can serve as an example. Frequency, as we know [7], is measured most accurately of all physical quantities. For its reproduction on the spot, a special computer-based MM was developed and implemented [8] introducing the "comb" effect [9].

Previously, in [10] to transfer the size of a unit of length from a working standard to an industrial MM, attention was focused on a laser interferometer, as an applied implementation of a working standard of a unit of linear size, and on an ultrasonic smart sensor that can serve as a sensor in robotics [11], where is used as a rangefinder [12]. Ultrasonic sensors are often used as rangefinders [13-15] with their specific drawbacks including insufficient accuracy.

2. Drawbacks

The main drawback is the lack of measurement accuracy, as it is caused by the negative effects of the environment in which the sound propagates. The parameters and values of the characteristics (the main one of which is the optical density) cannot be constant and have the ability to change during measurements. Limiting the measured distance to values from 3 cm to 40 cm is also considered an important drawback.

The following disadvantages of ultrasound sensors should also be noted. Surfaces with a porous structure absorb ultrasound well; therefore, it is difficult to measure the distance between them. If you have to measure the distance to a surface placed at an angle to the beam, or to a spherical surface, then the obtained results may turn out to be unreliable [16]. Directionality is an important characteristic of the sensor and is strongly influenced by the shape of the sensor: for an ultrasonic switch, it is 8° – 30°; the mode of vibration of the transducer, operating frequency, and type of transducer are selected to provide the required range.

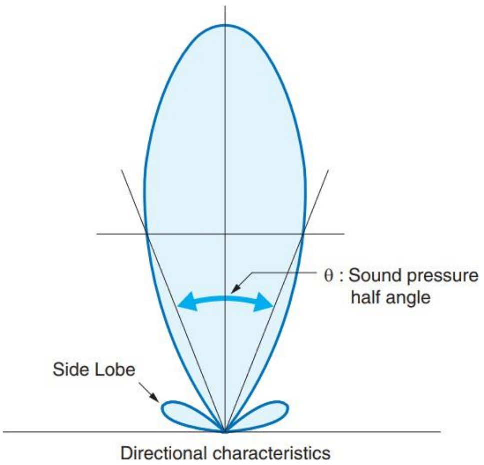

Fig. 1. Directionality of the radiation diagram of the ultrasonic sensor

Surfaces with a porous structure absorb ultrasound well; therefore, it is difficult to measure the distance between them. If you need to measure the distance to a surface placed at an angle to the beam, or to a spherical surface, the results obtained may turn out to be unreliable. The same problems await us when measuring the distance to a wall covered with foam. As a result, the errors of such rangefinders are 4 cm for the measured distance of 20 cm – 1400 cm [13] (or ~20 % error for a 20 cm distance), which seems to be insufficient for sensor usage in work.

These shortcomings require experimenters not only to consider the above-mentioned parameters while using ultrasonic range-finder sensors but also to ensure the metrological unity of measurements with their help, as well as to establish the accuracy of the described sensors. The latter can be achieved by developing metrological equipment for calibrating ultrasonic sensors.

3. Goal

The purpose of the work is to intensify the process of transferring the size of a unit of length in the range from 0.1 mm to 100 mm (secondary standards of [1, 3rd part]), where the standard includes special final measures of length from 3 mm to 100 mm, suitable for size transfer through working standards to industrial ultrasonic sensors by studying the metrological features of calibration.

4. Calibration of the ultrasonic sensor by a laser interferometer

Sensitivity, which is 0.5 mm for the UGT593 sensor from the IFM company, is also considered important [18]. Other metrological characteristics of this sensor: range of distances – 60 ... 800 mm with the size of the controlled object – 100 x 100 mm^2; "blind" zone – from 60 mm downwards; the drift of the detection point, i.e. relative detection error ± 2 % with a repeatability of readings of 1 % and a resolution of 1 mm. This means that the absolute detection error of a sufficiently large (100 x 100 mm^2) object is ±2 mm at a distance of 100 mm or ±1.2 mm at a distance of 60 mm. At a shorter distance, we fall into the "blind" zone, where multiple reflections of the acoustic signal lead to unreliable sensor readings. These shortcomings require experimenters not only to consider the above-mentioned parameters when using ultrasonic rangefinder sensors but also to ensure the metrological unity of measurements with their help. The latter can be achieved by developing metrological equipment for calibrating ultrasonic rangefinder sensors.

The calibration of the UGT593 ultrasonic distance sensor (Fig. 2) was carried out with the help of the LM20/50 laser interferometer of the SIOS company [19].

First, the indications of the ultrasonic sensor were studied by the method of self-analysis. The sensor was placed on a millimeter scale, to which a counting screen was attached. The sensor specifications state that the measurement range is 60 mm – 800 mm, and the output values are in mA, from 4 to 20. At the next stage of sensor testing, a standard rail was used to move the reflector. To direct the ultrasonic sensor to the rear wall of the reflector, the irradiation area was increased by attaching the 100 x 100 mm^2 partition to the rear wall of the reflector (Fig. 3). The optical beam from the laser interferometer was directed to the front wall of this same reflector.

Fig. 2. The design of the UGT593 ultrasonic rangefinder sensor

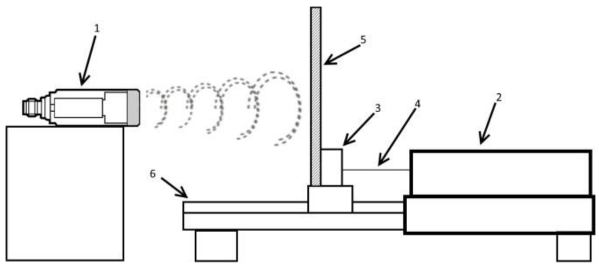

Fig. 3. Scheme of study of metrological characteristics of the ultrasonic sensor on the optical bench: 1 – sensor; 2 – interferometer; 3 – reflector; 4 – optical beam; 5 – partition; 6 – rail of the optical bench.

The sensor and interferometer were connected to the computer registration unit and data were recorded for 6 min. Every minute and a half, the reflector was moved to the maximum possible distance of 21 mm. Before starting the measurement with the help of a laser interferometer, the table and the optical bench were checked for the presence of vibrations. Checking the installation was done as follows: the mirror was placed at a distance of ~20 cm, and the interferometer was turned on. When starting the program, the distance between the mirror and the interferometer was reset to zero by software; then they recorded the readings of the interferometer, caused exclusively by the action of vibrational factors on the set. As a result of the analysis of the graph, it was concluded that the obtained data may be incorrect, since the method of fixing the reflective mirror with its oscillations, affects it. To eliminate this effect, a bearing was inserted into the attachment node and the interferometer was moved. This has lowered the vibration amplitude to the level of 0.01 μm. For comparison, the sensitivity threshold of the ultrasound sensor is ~100 μm.

Then the next problem was discovered – the drift of the laser interferometer readings. It was studied for 4 hours: it turned out to be stable over time at a velocity of ~1 μk per hour. During the four-hour measurement, changes in environmental conditions (temperature, pressure, humidity) were also recorded, as well as changes in the wavelength of laser radiation due to its automatic correction.

The relationship between the drift of impressions and the change in environmental conditions was studied. To do this, the temperature and wavelength of the interferometer were monitored simultaneously (Fig. 4). From the obtained results, it can be seen that the change in temperature affects the wavelength of the light generated by the interferometer laser: the effect is directly proportional.

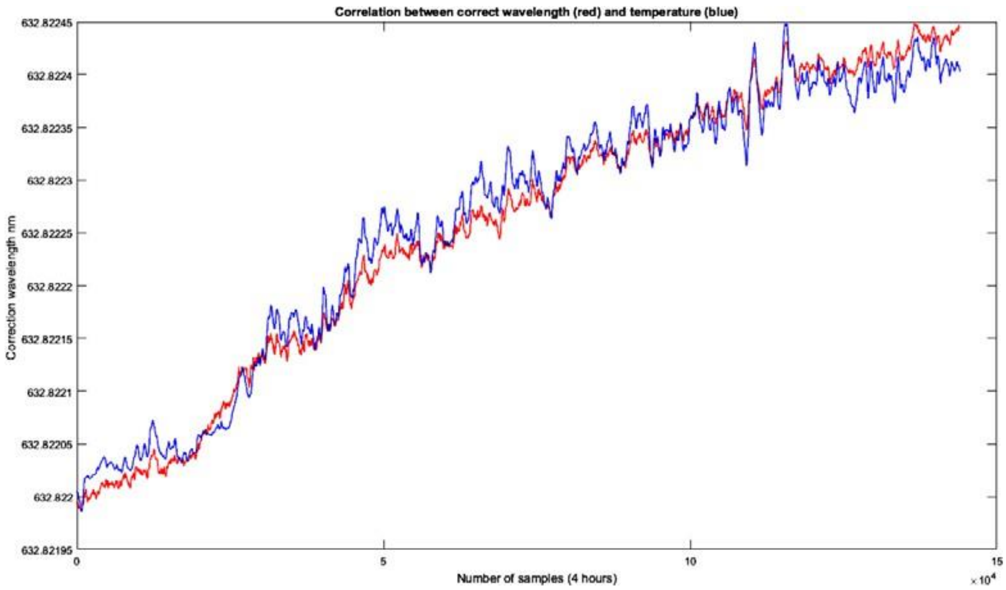

Fig. 4. The impact of the environment on the measurement results (blue color – temperature, red color – wavelength of the interferometer, monitored at the same time) [10].

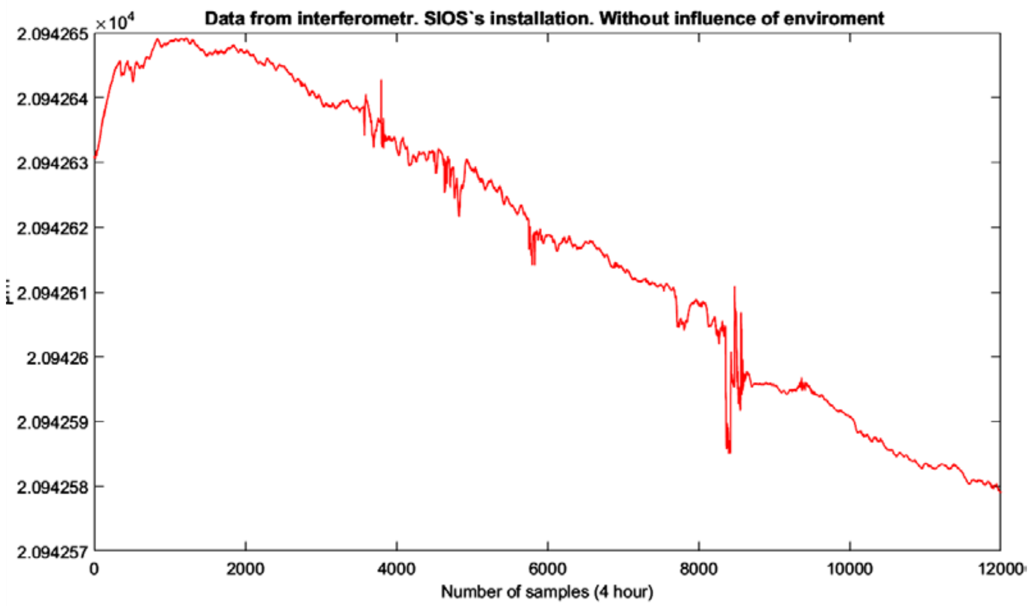

Fig. 5. Study of the change in readings for calibration without thermostatic [10]

Changes in the wavelength of the light generated by the interferometer laser were preliminarily estimated. The results of installation testing are shown in Fig. 5. As can be seen, the temperature causes a drift estimated as 10^{-7} nm in 3.5 h, which is insignificant when calibrating the ultrasound sensor with an interferometer.

As a result of conducting tests, the drift of the interferometer readings, as the working standard for calibrating the ultrasound sensor, did not exceed 1 μM. That is, the preparation of the developed installation based on the LM-20/50 laser interferometer with the main reduced error not exceeding 1 nM [20] and some additional errors totaling 1 μM, confirmed the possibility of its application for calibration of the ultrasonic sensor UGT593 [21]. The results of the studies, repeated 5 times, are listed in Tables 1 and 2.

Table 1. Results of calibration of the ultrasonic sensor using a laser interferometer (the first reference point is in the middle of the rail of the optical bench)

Number of calibration	Sensor's reading I_{iz}, mA	Interferometer reading l_{sz}, mm
1	6.63	0.0000002
2	6.63	0.0000001
3	6.63	0.0000003
4	6.63	0.0000001
5	6.63	0.0000001

Table 2. Results of calibration of the ultrasonic sensor using a laser interferometer (the second reference point – displacement from the first point)

Number of calibrations	Sensor's reading I_{iz} , mA	Interferometer reading l_{sz}, mm
1	5.76	21.0663187
2	5.76	21.0663163
3	5.76	21.0663137
4	5.76	21.0663109
5	5.76	21.0663085

Table 3. Converted results of ultrasonic sensor calibration while using a laser interferometer

№	Location of the reflector mirror at the zero point in the middle of the rail of the optical bench, mm		The shift of the reflector mirror from the zero point in the middle of the rail of the optical bench, mm			
	initial distance from the sensor to the back wall of the reflector liz	the initial distance from the interferometer to the reflector, lsz	minimal displacement of the reflector from the sensor, lid	maximal displacement of the reflector from the interferometer, lsd	distance li, by which the reflector was moved, according to the sensor data	distance l_S, by which the reflector was moved, according to the interferometer data
1	135.75	0.0000002	114	21.0663187	21.75	21.0663185
2	135.75	0.0000001	114	21.0663163	21.75	21.0663162
3	135.75	0.0000003	114	21.0663137	21.75	21.0663134
4	135.75	0.0000001	114	21.0663109	21.75	21.0663108
5	135.75	0.0000001	114	21.0663085	21.75	21.0663084

The values obtained from the ultrasonic sensor are given in mA. Therefore, you need to convert them into mm using a linear relationship: l_{iz}, mm = 70 + ((I_{iz}, mA – 4) · 400)/(20 – 4). Processing of the obtained results, in particular the 5th and 6th columns of the Table, is given below. First of all, at one point of the optical bench (for the same location of the mirror) we find the average value of the interferometer reading ls = 21.06631346 mm and the ultrasonic sensor li = 21.75 mm. The results of the transformation are recorded in Table 3. Next, we determine the calibration error of the ultrasonic sensor at one of the above-mentioned points of the optical bench repeating measurements at this same point five times: Δl = li – ls = 0.6836 mm; with the dispersion of the average value of the interferometer readings S = $1.65556\cdot10^{-11}$ mm; the RMS (Root-Mean-Square) deviation of interferometer readings is $S_1 = 4.06886\cdot10^{-6}$ mm; the uncertainty of interferometer readings U = $1.81965\cdot10^{-6}$ mm.

As a result of the 5-fold calibration of the ultrasonic sensor UGT593, its metrological indicators were determined, including the errors of distance measurement. For the size of the controlled object 100 x 100 mm^2, the RMS error of measurement was defined as 0.6836 mm or 3.5 % at a distance of ~21 mm.

Comparison with product data is following. The relative detection error specified by the manufacturer does not exceed 2 % with a repeatability of 1 % of readings and a resolution of 1 mm. This means that the absolute error of object detection is equal to 8 mm for a distance of 400 mm or 1.2 mm for a distance of 60 mm at a resolution of 1 mm. The RMS value of these two factors is 2.57 mm or 4.4 % for a distance of 60 mm.

5. Calibration methodology and use of other reference means

Unfortunately, the specified interferometer is a rather rare MM. In addition, the actual adjustment of both the optical bench and the laser interferometer is a long-term process, while the application of portable standards can significantly (several times) speed up the process. Therefore, regulatory documents recommend using special ring measures to transfer the size of a unit of length (p. 2.2.3.1 [1]). Also, bar length measures in the range from 0.001 mm to 1000 mm are proposed as working standards of the 2nd category for the calibration of working MMs.

The involvement of the partition as a reflector for the laser beam, on the one hand, as well as for the ultrasonic beam, on the other hand, introduces a significant systematic component of error due to differences in the zero-reference point of dimension, as well as the roughness of the reflecting surface. Errors caused by the slight rotation of the sensor while mounting it on the optical bench and, accordingly, its directionality of the radiation diagram, falling of certain areas of the directionality on shifted areas of the reflection surface, etc., are accumulated.

As a result of the occurrence of additional impact factors, the traceability of calibration results changes. There is a need to ensure that each calibration result obtained would be reported with the correct uncertainty value.

Finally, we focus on the calibration methodology: direct or indirect. The standard [1] mainly recommends the direct method. For the above-described calibration of ultrasonic sensors concerning the readings of the laser interferometer, the calibration method is defined as direct.

An indirect method of calibration is also recommended. Here, the interferometer is calibrated in advance and the distance to the screen is determined with its help. Then the interferometer is removed and a sensor to be calibrated is installed in its place on the optical bench. However, additional problems arise related to a) the point of attachment of the sensor to the optical bench, b) the attachment of the sensor; c) the appearance of a new type of error, and, accordingly, the appearance of an additional component of measurement uncertainty caused by a possible shift in the position of the sensor relative to the previous location of the interferometer; c) with re-attachment of the interferometer on the optical bench during calibration at the next point of the scale and so on.

Therefore, the method of simultaneously deploying a laser interferometer and an ultrasonic sensor to the rail of an optical bench is accepted in the issue. Here, the optical radiation of the laser and the sound signal of the sensor simultaneously act on the screen installed between the two MMs, the position of which is perceived as a conditional zero. The distance to the screen is determined. If an error occurs at one point of the scale, it is considered as consisting of systematic and random components. The first of them is eliminated or minimized during the analysis of the results, and the second one serves as a basis for calculating the RMS deviations characterizing the quality of measurements according to [22].

Moreover, the approach of eliminating the systematic component of error in the form of bias was previously considered in the work [23] and justified as an approach to combining the two parameters "inaccuracy" and "bias" into a complex characteristic parameter that describes the general deviation of the measurement from the target value. It is shown how the established maximum permissible values of error and bias can be transformed into a new maximum permissible value for a new inspection parameter, considering the experience with the pre-established needs, as well as the technical limitations to meet these requirements.

Reducing the two control rules for “bias” and “error” of the results to one common parameter can be considered as a clear simplification of the evaluation procedure, which, however, provides certain flexibility to fulfill the requirements. So, in our case, there may arise an additional component of error and, accordingly, the uncertainty of the obtained results, due to the uneven thickness and unevenness of the screen with its possible displacement relative to the centering and rotation of the axes of the laser and ultrasound beams. Therefore, the profile of the screen was additionally studied, taking into account the work [24].

It should be noted that the rationale for the introduction of a new complex control parameter is the provision of the theory of processing measurement results [25]. According to it, the variance D of a random variable X is the mathematical expectation of the square of the deviation of this value from its mathematical expectation (average value). The variance is invariant to changes in the shear/displacement coefficient. Thus, adding a constant to the values of the random variable does not change the variance:

$$D(X + a) = D(X) \quad (1)$$

On this basis, an approach for the validation of individual measurements of the control sample was proposed. It enables rapid evaluation and is better suited to detect critical measurement deviations as early as possible and can be adapted to define custom control rules using control samples with known target values.

5.1. The root-mean-square deviation approach

In this work, we implemented the approach based on RMS deviations, which, on the one hand, corresponds to the provisions of [26-27], and, on the other hand, is effectively developed in [23]. Optimization of the uncertainty calculation procedure during the calibration of ultrasound sensors and working standards while processing of results was carried out following the Guidelines for the evaluation of measurement uncertainty [26-27]. First, the uncertainties of the calibration coefficient and the sensitivity of the MM characteristics at each calibration point were calculated. For this, the standard uncertainties of the input above-mentioned values were estimated.

The uncertainty associated with the dispersion of readings of the MM being calibrated was calculated by type A according to the well-known formula:

$$\frac{u_A(\bar{X}_i)}{\bar{X}_i} = \frac{1}{\bar{X}_i}\sqrt{\frac{1}{(n-1)}\sum_{i=1}^{n}(X_i - \bar{X}_i)^2} \times 100 \quad (2)$$

$$\bar{X}_i = \frac{1}{n}\sum X_i \ , \quad (3)$$

here X_i was the result of individual observations; $\bar{X}_i$ was the average value of multiple observations. Other uncertainties are determined by type B.

The uncertainty introduced by the working standard:

$$\frac{u_B(H)}{H} = \frac{U_{et}}{2}, \quad (4)$$

here U_{et} is an expanded uncertainty of the reference value from the calibration/product certificate or previous studies. The uncertainty of the distance correction factor is calculated by:

$$\frac{u_B(k_{rr})}{k_{rr}} = \frac{0,2}{r}, \quad (5)$$

here r is the distance, m. We accept the input values as uncorrelated. In the following, the total standard uncertainty of the calibration coefficient for the direct calibration method is calculated, and the uncertainty budget is summarized in Table 4.

Table 4. The budget of uncertainty

Input quantity	Assessment of input quantity	Standard uncertainty, %	Type of uncertainty
X1 – ambient temperature			A
X2 – environmental humidity			A
X5 – the distance between the screen and the interferometer			B
X6 – the scattering angle of the sensor's directionality			B
X7– the scattering angle of the screen's directionality			B
X8 – the limits of the deviation angle of the screen mounting			B
X9 – distortion of the sensor reception signal by multiple reflections			B
Output quantity	Measurement result	The average standard uncertainty, %	Extended uncertainty, %, while k=2, P=0.95

Calculation of the total standard calibration uncertainty for direct measurements:

$$\frac{u(N)}{N} = \sqrt{\left(\frac{u_A(X)}{X}\right)^2 + \left(\frac{u_B(H)}{H}\right)^2 + \left(\frac{u_B(h)}{h}\right)^2 + \left(\frac{u_B(k_t)}{k_t}\right)^2 + \left(\frac{u_B(k_{rr})}{k_{rr}}\right)^2 + \left(\frac{u_B(k_T)}{k_T}\right)^2} \quad (6)$$

The uncertainty budget is given in Table 5.

Similarly, the total standard uncertainty of calibration for the indirect calibration method is calculated. The uncertainty budget is given in Table 6.

Calculation of the calibration uncertainty of the working standard

Here, the uncertainty of the calibration of the working standard – the laser interferometer – changes slightly compared to the direct calibration method, since the process is significantly stretched in time due to the need to constantly (at each calibrated point) reinstall either the standard MM or the calibrated sensor on the optical bench. The uncertainty associated with the dispersion of readings of the working standard used during calibration is calculated by type A, other uncertainties are determined by type B (Table 7).

Table 5. The budget of uncertainty

Input quantity	Assessment of input quantity	Standard uncertainty, %	Type of uncertainty
X1			A
X2			B
X3			B
X4			B
X5			B
X6			B
Output quantity	Measurement result	The average standard uncertainty, %	Extended uncertainty, %, while k=2, P=0.95

Table 6. The budget of uncertainty

Input quantity	Assessment of input quantity	Standard uncertainty, %	Type of uncertainty
X1			A
X2			A
X3			B
X4			B
X5			B
X6			B
X7			B
Output quantity	Measurement result	The average standard uncertainty, %	Extended uncertainty, %, while k=2, P=0.95

Table 7. The budget of uncertainty

Input quantity	Assessment of input quantity	Standard uncertainty, %	Type of uncertainty
X3 – laser temperature, outside			A
X4 – time effects of the laser			A
X8 – the limits of the deviation angle of the screen mounting			B
X9 – distortion of the reception signal by multiple harmonics			B
Output quantity	Measurement result	The average standard uncertainty, %	Extended uncertainty, %, while k=2, P=0.95

6. Conclusions

1. The possibilities of direct and indirect methods of calibrating the working measuring mean of distance measurement – the ultrasonic sensor – have been studied. According to the results of laboratory testing, it was established the feasibility of the application of a direct calibration method when transferring the size of a unit of length, from a laser interferometer, as a working standard of the 2nd category, to the mentioned sensor.

2. According to the manufacturer of the studied sensor UGT593, the absolute error of setting the distance to the object is ± 8 mm at a distance of 400 mm or ± 1.2 mm at a minimum distance of 60 mm with a resolution of ±1 mm. The RMS value of the 2 factors is ± 2.57 mm or ± 4.4 % for a distance of 60 mm. Following the results of the calibration, the limit value of the absolute error of the calibrated MI is ± 0.6836 mm at a distance of 20.2 mm with a resolution of 1 µm. So, the RMS value of the 2 factors is

unchanged which is ± 3.3 %. Otherwise, the accuracy of the ultrasonic sensor calibration increased by 25 % (the RMS values have decreased from 4.4 % to 3.3 %). This emphasizes the correctness of the chosen methodology and the selection of MIs for transferring the size of a unit of length from the working standard to the working mean, even in its "blind" zone.

3. It is shown that the direct method of transferring the size of a unit of length from the laser interferometer to the ultrasonic sensor requires significant time costs. While performing, it seems to be easier and faster to comply with the transfer of the size of a length unit by the mentioned method. However, to improve the quality of calibration and eliminate the systematic component of the error, the set values of the error and bias should be converted to a new permissible value of another verification parameter. Reducing the "bias" and "error" of the results to a common parameter can be considered a clear simplification of the evaluation procedure, which provides a certain flexibility in the fulfillment of the requirements. This is justified by the position of the theory of processing measurement results, according to which the variance of a random variable is invariant to changes in the "bias", i.e., adding a constant to the values of a random variable does not change its variance.

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2. Conflict of interest

There are no conflicts of interest during the writing, preparation, and publication of the article, as well as mutual claims of co-authors.

References

[1] DSTU 3741:2015. Metrology. State verification scheme for means of measuring length, 2015 (in Ukrainian). https://online.budstandart.com/ua/catalog/doc-page?id_doc=61978

[2] M. Nadi, C. Marco, M. Kouider, J. Prado, and D. Kourtiche, Embedded system design and implementation of standard auto-calibrated measurement chain, Int. Journ. on Smart Sensing & Intel. Systems, vol.1, No.1, March 2008, pp.21-33. https://www.researchgate.net/publication/26850144_Embedded_system_design_and_implementation_of_standard_auto-calibrated_measurement_chain/fulltext/0e6058e4f0c46d4f0ab335a8/Embedded-system-design-and-implementation-of-standard-auto-calibrated-measurement-chain.pdf

[3] F. M. Mirzaei. Extrinsic and Intrinsic Sensor Calibration. A Diss-n Submit. to Faculty of Grad. School of Un-ty of Minnesota, 2013 https://core.ac.uk/download/pdf/76345447.pdf

[4] The Quantum Hall Effect, M.E. Cage, K. Klitzing, A.M. Chang, F. Duncan, M Haldane… – 2012 – books.google.com

[5] Cyber-Physical Systems and Metrology 4.0. Co-editors S. Yatsyshyn, B.Stadnyk, 2021, IFSA Publishing. https://books.google.com.ua/books/about/Cyber_Physical_Systems_and_Metrology_

[6] W. Nawrocky, Quantum Voltage Standard, in Introduction to Quantum Metrology, pp 85–118, https://link.springer.com/chapter/10.1007/978-3-030-19677-6_4

[7] Nat. Phys. Lab., Time and Frequency, https://www.npl.co.uk/products-services/time-frequency

[8] D. Gajski, S. Abdi, A. Gerstlauer, G. Schirner, Embedded system design, Modeling, Synthesis and Verification, Springer, 2009. https://www.cin.ufpe.br/~rab/Gajski %20D.D. %20et %20al. %20Embedded %20System %20Design %20- %20Modeling, %20Synthesis %20and %20Verification %20(Springer, %202009)(1441905030).pdf

[9] I. Köchert, "Ultrastable metrology laser at 633 nm using an optical frequency comb". In: Optical Micro-and Nanometrology VII. International Society for Optics and Photonics, p. 106780S, 2018. https://doi.org/10.1117/12.2306907

[10] S.Yatsyshyn, I,Nazarkevych, R.Mastylo, MEM, Calibration of the Ultrasonic Sensor-Range Finder by the Laser Interferometer, vol.81, No.4, pp. 10-17, 2020, https://science.lpnu.ua/istcmtm/all-volumes-and-issues/volume-81-no4-2020/calibration-ultrasonic-sensor-range-finder-laser

[11] Types of Robot Sensors. https://www.javatpoint.com/types-of-robot-sensors

[12] Law of Ukraine "On Metrology and Metrological Activities" dated June 5, 2014 № 1314 – VII, (in Ukrainian). https://www.rrt.ua/govsupport/ index/lawsone/lang/uk?id=94

[13] DSTU 2681-94 Metrology. Terms and definitions. With Amendment (IPS No. 8-96), State Standard of Ukraine, 1994. (in Ukrainian). https://dtp.lg.ua/Dokumentacija %20i %20oformlenie/DSTU_2681-94_metrologiya._terminy_i_opredeleniya.pdf

[14] PEKO prospectus https://peko.com.ua/distance-sensors/ultrasonic-distance-sensors

[15] Bosch company prospectus. https://www.automaster.net.ua/artykuly/ultrazvukovi-datchiki-bosch-6-pokolinnya-vzhe-dostupni-v-ukrayini,55525

[16] L.L. Beranek, "Acoustical measurements," AIP, Woodbury, NY, 1988. https://www.phon.ucl.ac.uk/home/dept/library/pling.htm

[17] V. Magori, "Ultrasonic sensors in air," IEEE Ultrasonic symposium, Proceedings, pp. 471-481 (1994). • DOI:10.1109/ULTSYM.1994.401632

[18] IFM products prospect https://www.ifm.com/ua/uk/product/UGT593?tab= details

[19] Metrology and Measurement Technics. Editor Ye. Polishchuk, Lviv, «Beskyd-Bit», 2003 https://librarygo.lpnu.ua/?elbook=metrologiya-ta-vymiryuvalna-tehnika

[20] H. Zhang, J. Wang, C. Guo, Tool Frame Calibration for Robot-Assisted Ultrasonic Testing, Sensors, 2023, 23, 8820. https://doi.org/10.3390/s23218820 https://www.mdpi.com/journal/sensors

[21] S.P. Yatsyshyn, B.P. Yatsyshyn. Fire detectors as means of information and measurement technology, Bulletin of LSU life safety, No.4, 2010, pp.70-74. (in Ukrainian). https://media. neliti.com/media/publications/388792-none-dc7bba2f.pdf

[22] M. Mykiichuk, Metrological support of production, Lviv, Ukraine, Lviv Polytechnic Publishing House, 2017. (in Ukrainian), https://vlp.com.ua/node/17379

[23] Trends in quality in the analytical laboratory. I. Traceability and measurement uncertainty of analytical results, July 2004, TrAC Trends in Analytical Chemistry 23(7):480-490, DOI: 10.1016/S0165-9936(04)00733-2, Authors: Isabel VJ Taverniers, Marc De Loose, Erik Van Bockstaele https://www.researchgate.net/publication/222426151_Trends_in_quality_in_the_analytical_laboratory_I_Traceability_a nd_measurement_uncertainty_of_analytical_results

[24] Jung-Hwan Kim, Advanced measurement and diagnosis of the effect on the underlayer roughness for industrial standard metrology, Scientific Reports, vol. 9, Article number: 1018, 2019. DOI:10.1038/s41598-018-36991-z https://www.researchgate.net/publication/330759880_ Advanced_measurement_and_diagnosis_of_the_effect_on_the_underlayer_roughness_for_industrial_standard_metrology

[25] M. Dorozhovets, Processing of measurement results, Lviv, Ukraine, Lviv Polytechnic Publishing House, 2007, (in Ukrainian)

[26] COOMET R/GM/32:2017. Calibration of measuring instruments. Algorithms for processing measurement results and estimating uncertainty. https://easc.by/novosti/448-13- noyabrya-2023-goda-provedeno-23-rg-odm-ntkmetr

[27] Publication Reference EA-4/02 M:2022 Evaluation of the Uncertainty of Measurement in Calibration, 4th April 2022. https://www.accredia.it/en/documento/ea-4-02-rev-03- evaluation-of-the-uncertainty-of-measurement-in- calibration/