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Traceability Assurance Method for Measurements Performed Using Hybrid Measuring Systems Consisting of Tactile and Optical Devices

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ABSTRACT

This paper presents new method for traceability assurance of measurements performed using hybrid measuring systems built using one system that is based on tactile point measurement method (for example: coordinate measuring machine, articulated arm coordinate measuring machine, laser tracker system) and the second one that is based on optical field measurement method (for example: structured light scanners, digital image correlation systems). Within works described in this paper a series of tests aimed at determining task-specific errors for measurements performed using such composed systems were run. Measurement tasks for which such errors were determined include length measurements and measurements of form deviations (roundness, flatness, etc). Measurements were performed using material standards representing various shapes, dimensions and geometric relations. Measurements were run in different orientations and positions of the standards. Types of standards along with orientations and positions used were chosen basing on the guidelines of the ISO 10360 standard, parts 2, 5, 7, 8, 9, 10, 12, VDI/VDE 2634 and longtime experience of authors of this paper. At the end, results of performed measurements were checked for consistency with results of material standards calibration and values of task- specific maximum permissible errors were established. Guidelines for using developed method in other hybrid systems were also presented in the paper.

Keywords: multisensor systems, hybrid systems, traceability, calibration, uncertainty.

INTRODUCTION

The development of coordinate measuring technology in recent years has been driven by several trends towards which changes and the continuous evolution of measurement systems are directed. The last decade can be remembered as a period of incredible growth in 3D scanning techniques, which are becoming increasingly common, more affordable, and often more accurate, frequently becoming the preferred measurement method in many situations not only within the industry but also in fields such as medicine [1, 2], heritage conservation [3, 4], and even the entertainment industry [5, 6]. This is understandable, considering the advantages of scanning techniques, which primarily include the ability to obtain coordinates of hundreds of thousands or millions of points describing the geometry of the measured object in a very short time. Nevertheless, certain limitations of non-contact methods have been known for many years, which in current technical solutions are not satisfactorily addressed. These include primarily difficulties in scanning of: sharp edges, internal dimensions, and reflective surfaces [7, 8]. To overcome these limitations, scanning techniques are often combined with tactile methods. A very popular solution are multi-sensor measuring systems [9–11], which allows the point acquisition process to be performed by various probing systems installed on the same device. Another approach of combining contactless and tactile measuring methods is hybrid measuring systems, which consist of separate devices integrated in such a manner that they can measure in a common coordinate system. This group is particularly interesting as it enables the development of a measurement system with functionalities beyond the capabilities of the individual systems which creates the hybrid system, without the need for often significant investments in upgrading the component systems with new sensors. Additionally, hybrid systems sometimes enable the combination of systems that are rarely, if ever, found in the offerings of companies that provide services in the production and distribution of coordinate measuring systems, for example combination of a stationary CMMs (coordinate measuring machines) with a structured light scanners.

Several hybrid coordinate measuring systems have been described in literature so far. Zexiao et al. [12] described hybrid coordinate system that comprises a CMM, a 3d structured-light scanner and a rotary table. In described hybrid system the scanner was mounted on the z-axis ram of the CMM while rotary table was installed on the table of machine. Merging coordinate systems of all devices involves measurements of reference objects such as reference ball and cylinder. The authors of the article studied accuracy of the presented hybrid system. They distinguish four main contributors that affect the accuracy of whole system: accuracy of CMM equipped with touch trigger probe, accuracy of structured light scanner, accuracy of data patches assembling and data merging. They propose different tests to assess influence of each of mentioned contributors on the measurement results, which involved measurement of different material standards including measurements of flatness of reference plane, measurements of reference cylinder and reference ball. The authors reported that the worst results were obtained during tests on random errors of structured light scanner. Overall accuracy of presented hybrid system can be described by giving ranges describing system's systematic errors and random errors, which in case of second group is sum of range of random errors of CMM with touch trigger probe and random errors of structured light scanner. Sładek et al. [13] presented another example of hybrid coordinate measuring system. It consists of bridge type CMM with movable table and structured light scanner installed outside CMM measuring volume. Unification of both devices coordinate systems are done by measurements of ball plate standard which should be firstly measured by CMM and then by the 3d scanner in order to find the transformation matrix that allows to bring indications of both devices into the common coordinate system. Hybrid system presented in considered article primarily uses 3d scanner for measurements, giving the dense cloud of point as a measurement result. Next obtained cloud is segmented on the basis of measured object geometry and searched for holes and scan discontinuities. If such areas are detected or if higher accuracy is needed the measurements of selected areas are performed with CMM. Authors checked accuracy of developed hybrid system by performing test based on guidelines presented in normative documents on testing tactile CMMs [14] and 3d scanners [15]. Paper delivers only brief information about length measurement error determination procedure which involved measurements of ball-plate standard in eight positions. Reported accuracy of length measurement was similar to accuracy of utilized structured light scanner. Another example of hybrid coordinate measuring system was presented by Li et al. [16]. The described system include typical bridge-type CMM, structured light scanner and AACMM (articulated arm coordinate measuring machine) installed close to CMM measuring volume. Article focus mainly on developing novel method for coordinate systems unification for all mentioned components of hybrid station. New standard was proposed, which is a variation of the classic ball plate standard, consisting of 9 balls arranged on a common base in groups of three to form three triangles. The coordinate system unification procedure begins with measuring the centers of the balls on the standard. Then, for each group of three balls, a triangle is defined from their centers, and in the next step, its centroid is determined. With the three centroids determined in this way, an another triangle is formed which vertices are used to determine the translation and rotation matrix describing connection between the coordinate systems of the scanner and the AACMM with the CMM system treated as the reference.

Authors compare their coordinate systems unification method with traditional approach based only on measurements of reference balls and usage of their center points for merging coordinate systems and report significant improvement of accuracy of entire unification process in case of developed method, mainly due to double averaging of contactless methods errors with centroid determination. Different example of hybrid measuring system was shown by Kaisarlis et al. [17]. Hybrid system described there combines ITS (industrial total station) with AACMMs and was developed for large scale measurements. Again article focus mainly on description of coordinate system unification method which this time was achieved using hidden point bar tool which is reference element typically used for Total Stations. However, construction of reference object of this type makes them not suitable for direct measurements with AACMM. Authors described potential measurement strategy which enables determination of the same points with both considered devices and then their usage for obtaining transformation matrices. They also showed application example of described method analysing errors of merging process but give no information on accuracy of hybrid system treated as whole.

The literature review indicates that previous studies on hybrid measurement systems mainly focus on the issue of integrating the coordinate systems of different devices comprising the hybrid system. This issue is also widely discussed in the case of multi-sensor systems and is addressed in numerous publications [18–20]. Data fusion from different sensors is problematic for various reasons, primarily due to the different operating principles of individual measuring devices. This results with issues with different data sets resolutions and accuracies of their measurements. Another issue observed in articles on hybrid systems is the problem with measurements traceability assurance which should be achieved through appropriate calibration. Currently, normative documents are available for most types of coordinate measuring systems. However, in the case of hybrid systems, it is not clear how to translate the accuracy information of individual system components into the overall accuracy of the entire hybrid system, especially for measurement tasks that utilize data obtained from different systems. This subject is studied and described in this article. The following sections presents developed hybrid measuring system and its operation principle as well as procedure of calibrating system of such type. The presented methodology is based on the series of ISO 10360 standards and VDI/VDE 2634 guidelines which have been studied and adapted to match the characteristics of the developed hybrid measuring system.

Creating and installing large-scale engineering structures, which often need to be manufactured with narrow tolerances, requires performing accurate measurements over long distances. These measurements pose a considerable challenge for metrology specialists responsible for maintaining product quality, especially in the energy, aerospace, automotive, and machinery industries. Contact measurements are time-consuming due to the necessity of moving measurement probes over long distances. Optical measurements are much faster, but their measurement range rarely exceeds a few meters. To accumulate the advantages of both mentioned measurement methods, hybrid measurement systems (HMS) can be used. Of course optical systems and tactile measuring methods differ in several aspects. The most important ones are presented in Table 1 which summarize crucial differences between tactile CMMs and structured light scanners:

Due to these differences, in order to leverage the advantages of both methods, the concept of a hybrid measurement system was developed, comprising a coordinate measuring machine and a structured light scanner.

MATERIALS AND METHODS

The hybrid measuring system comprising large scale CMM and 3d scanner

The HMS described in the article is designed for measuring the 3D geometric features of static objects by mapping the surfaces of the measured parts with sets of coordinates of points lying on the surface of object. These coordinates should be obtained by the systems comprising the HMS. The hybrid system (Fig. 1) is based on the use of Hexagon's precise PMM-G 50.30.20 coordinate measuring machine and REVOPOINT's structured light scanner (model 3D Scanner MINI), combining the advantages of both systems.

The first stage of the measurements performed using HMS involves defining a common coordinate system for both measuring devices. It is assumed that the less accurate measurement

Table 1. The most important differences between tactile and contactless coordinate measuring methods presented on the example of tactile CMM and structured light 3d scanner

Characteristics	Tactile measurements	Contactless measurements
Measurement duration	Very slow in point-to-point mode, faster in scanning mode but still needs a lot of time to obtain dense cloud of points	Hundreds thousands or millions points can be obtained in few seconds
Measurement accuracy	Enable the measurement of individual points with uncertainties below 1 µm	Typical accuracy of tens of micrometres for single measurements. Merging scans obtained from different directions usually lowers their accuracy .
Mobility	Not portable. Transportation involves additional adjustment and calibration	Usually can be easily transported. Often the measurement requires moving them around the measured object
Cost	Expensive. Usually needs special rooms (with air-conditioning, access to compressed air and solid foundations) for proper functioning	Differs with accuracy and functionalities of system. Can be very cheap. Even most accurate scanners are usually cheaper than CMMs
Invasiveness	During contact of probe tip with surface of measured object may potentially damage or deform the material	Can measure soft and delicate materials, parts made of plastics, and conduct anthropometric and medical measurements without applying pressure
Coordinate system alignment	May accurately establish a single local coordinate system based on measured object geometry	May encounter challenges in accurately establishing the origin of the coordinate system and require multiple views from different angles to fully reconstruct the object, operating in several local coordinate systems that are merged into a single global coordinate system
Influence of measured object characteristics	Non-sensitive to surface characteristics. Potential problems with probe radius compensation during measurements of freeform surfaces	Particularly sensitive to parameters such as colour, gloss, and surface texture, which can complicate measurements for materials like glass, marble, steel, plastic, and materials with dark, polished, rough, or variable reflective properties. May struggle with precise edge, non-continuous element, and hole measurements

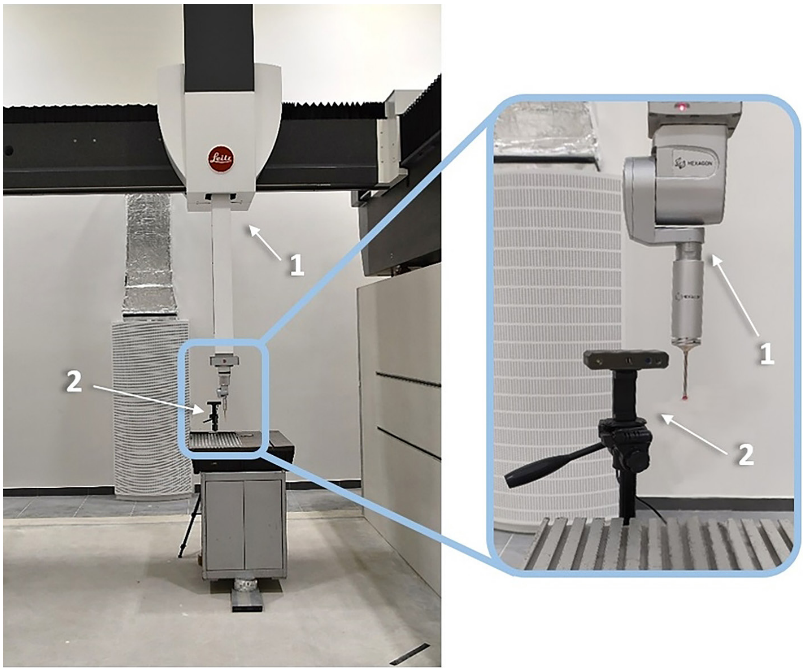

Figure 1. The hybrid measuring systems described in article consisting of: 1) gantry type0 CMM; 2) structured light 3d scanner

system (structured light scanner) should adopt the coordinate system of the more accurate machine (CMM). This can be accomplished by measuring reference object consisting of three spheres using both measuring systems included in HMS. Both systems should measure in their basic coordinate system. Then it is possible using best-fit algorithm to find the relation between those two coordinate systems described by the translation matrix of origin point and rotation matrices of coordinate axes in relation to each other. The transformation of coordinates can be done using equation (1):

$$\begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = Tr \cdot R_z \cdot R_y \cdot R_x \cdot \begin{bmatrix} x' \\ y' \\ z' \\ 1' \end{bmatrix} \quad (1)$$

where: x,y,z – coordinates given in common coordinate system of HMS (the coordinate system of CMM); x', y', z' – coordinates given in 3d scanner coordinate system; T_r – translation matrice; R_z, R_y, R_x – rotation matrices.

In the next stage of the measurements, a local coordinate system is defined on the measured object. If possible, the geometric features on the measured object which are used for local coordinate system definition should be obtained using the point-based method, to ensure higher measurement accuracy. Subsequently, the object is measured in this coordinate system by the structured light scanner. In the following stage, the point cloud obtained from the measurements is analyzed. The result of this analysis is the segmentation of the point cloud into areas representing basic geometric features (planes, cylinders, cones, spheres, etc.) and freeform surfaces. In the final step, the segmented point cloud is transferred to metrological software to assess dimensions or to check the deviations between actual surface of object and its CAD model.

Additionally the described hybrid system utilizes a data fusion method which was developed specially for it. The first stage of this method is uniform reduction of the point cloud by 28%. This value was determined in the following way. In the first step, measurements of reference objects with different shapes (sphere, plane, ball-bar standard) were performed using a system based on field methods with a large number of measurement points (without point cloud reduction; only points clearly originating from background objects, such as those collected on the measurement table, were removed). In next steps, the number of measurement points was reduced (point cloud simplification). The simplification was carried out in software where it is not possible to directly specify by what percentage the points cloud should be simplified, but it is possible to set the level of simplification strength (ranging from 1 to 8). For each obtained simplified point cloud, the

Table 2. The results of point cloud reduction obtained for the four measurement tasks: measurement of sphere diameter, measurement of sphere form deviation, measurement of the distance between two spheres on a ball-bar standard, and measurement of the flatness deviation of a reference plane. The value of simplification, highlighted in bold type, indicates the last level that does not exceed the accepted threshold for measurement accuracy degradation for the given measurement task

Measurement task							
Sphere diameter		Sphere form deviation		Distance		Flatness	
Cloud simplification by, %	Deviation relative to the reference value, mm	Cloud simplification by, %	Deviation relative to the reference value, mm	Cloud simplification by, %	Deviation relative to the reference value, mm	Cloud simplification by, %	Deviation relative to the reference value, mm
0	0.0438	0	0.0935	0	0.0252	0	0.0552
15	0.0476	15	0.0949	15	0.0248	19	0.0575
28	0.0481	**28**	0.0962	28	0.0272	**32**	0.0597
38	0.0534	38	0.0975	38	0.0349	44	0.0619
48	0.0583	48	0.0985	48	0.0412	53	0.0644
56	0.0651	56	0.1012	**56**	0.0435	61	0.0667
62	0.0703	62	0.1030	62	0.0454	67	0.0680
69	0.0753	69	0.1060	69	0.0478	73	0.0697
74	0.0761	74	0.1067	74	0.0533	77	0.0723

results were compared with those recorded in the calibration certificates of the reference objects (for shape measurements, a reference value of 0 mm was assumed). The goal of this phase was to determine the percentage of points obtained from the scanning system (relative to the number of points in the cloud directly resulting from the measurement) by which the number of points could be reduced without significantly degrading the results (a 10% deterioration in the deviation value, compared to the result for the scan with the highest number of points, was set as the threshold indicating excessive result degradation based on the calibration certificate values). Table 2 presents the results of point cloud reduction obtained for the four measurement tasks performed: measurement of sphere diameter, measurement of sphere form deviation, measurement of the distance between two spheres on a ball-bar standard, and measurement of the flatness deviation of a reference plane.

The acceptable threshold for measurement accuracy degradation is reached at different percentages of point cloud simplification for various measurement tasks. However, the conducted measurements established that for all considered measurement tasks, the acceptable threshold for accuracy degradation is not exceeded with a 28% reduction in points. This level of point reduction has been adopted in the developed data fusion method.

The second stage of developed data fusion method is responsible for increasing the accuracy of measurements conducted using contactless method based on the results of more accurate point-based method. This part of method relies on measuring by both systems the reference elements which should be located around the measured object prior the actual measurements of inspected workpiece. Spheres, circles, or cones can be used for this purpose as a elements which can define specified reference point. This reference point should be determined using both measurement methods included in HMS. Next, a vector can be calculated, with its starting point set at characteristic point of the reference element determined using the contactless method, and its endpoint set in characteristic point of the reference element determined using the tactile method. This process is performed for all reference elements located around the measured workpiece. In the next step, all points in the point cloud obtained with the contactless method are translated by the vector described previously, determined for the reference element closest to the considered point in the point cloud. The results of studies conducted on described method showed that this procedure improves accuracy of HMS measurement (expressed as a deviation of measurement result from value given in calibration certificate of measured artefact) even up to several percent (depending on the considered measurement task).

Method for ensuring traceability of hybrid measuring system

The proposed method for ensuring traceability of HMS is based on the analysis of available standardization documents related to calibration of coordinate measuring systems, including the ISO 10360 series of standards: part 2 (tests for CMMs used for measurements of linear dimensions [14]), part 5 (tests for CMM's tactile probing systems [21]), part 7 (tests for CMMs equipped with imaging sensors [22]), part 8 (tests for CMMs equipped with optical distance sensors [23]), part 9 (tests for CMMs equipped with multiple probing systems [24]), part 10 (test for laser trackers [25]), part 12 (tests for Articulated Arm CMMs [26]); as well as the VDI/VDE 2634 recommendations (describing tests for optical 3d measuring systems based on area scanning [27]). As a result of analysis of mentioned documents four tests have been proposed which should ensure consistency of the HMS with the primary unit of length. The proposed tests include:

1. Verification of the point acquisition systems separately for both measurements methods included in the HMS:
   - reference element: sphere – made of material which allows tactile and contactless measurements
   - number of positions: 3 positions for tactile measurements and 3 positions for contactless measurements
   - procedure description: test is aimed at checking if the individual components of the HMS works properly and their indications are within MPE specified by the manufacturer or calibration certificates. Sphere should be measured in three selected locations within the measurement volume of the tactile system, each time performing a measurement of 25 points on the surface of the standard. It is recommended that points would be arranged in a manner specified in [21]. Measurements lead to determination of the form deviation of

the measured sphere (relative to the best-fitted element determined using the Gaussian least squares method) and the dimensional deviation relative to the dimension specified in the calibration certificate of the spherical standard. For the contactless method, measurements should be taken in three selected locations within the HMS measurement volume, evaluating the same parameters, but without limiting the number of points used to determine the best-fitted element

2. Verification of the combined operation of the point acquisition systems included in the HMS:

- reference element: sphere - made of material which allows tactile and contactless measurements
- number of positions: 3 positions in measuring volume of HMS
- procedure description: the test should be performed in three selected locations within the HMS measurement volume, each time the evaluated parameters are form deviation of measured standard and diameter deviation in relation to calibration certificate of sphere. However, this time, the measurement of the spherical standard is performed using both systems simultaneously, and the developed data fusion method (described in last paragraph of section "The Hybrid Measuring System comprising large scale CMM and 3d scanner") is used to determine the measurement results obtained using the HMS. The possible locations of standard which can be used during this part of tests are shown in Figure 2.

3. Verification of the length measurement error:

- reference element: length standards which can be measured using tactile and contactless methods, preferably ball-bar standard
- number of positions: 7 positions in measuring volume of HMS
- procedure description: the test involves measurements in seven different positions within the HMS measurement volume of one selected length. Not only the position should be changed but also the orientation of the length standard. The recommended orientations include: three orientations along the x, y, and z axes of the HMS measurement volume; two orientations along two spatial diagonals of the HMS measurement volume; two orientations along selected diagonal planes (xy, yz, or xz) of the HMS measurement volume. The length error is determined each time as the difference between the measurement result obtained using HMS (obtained using the data fusion method described in last paragraph of section "The Hybrid Measuring System comprising large scale CMM and 3d scanner") and the length value represented by the standard, as read from the calibration certificate. The possible locations of standard which can be utilized during tests on accuracy of length measurements are shown in Figure 3.

4. Verification of the error of flatness and roundness measurement

- reference element: the flatness standard and the reference ring
- number of positions: 7 positions in measuring volume of HMS
- procedure description: test is conducted in seven different positions within the HMS measurement volume. The measurements are performed on the flatness standard and the ring gauge. The evaluated parameters include form deviations relative to the best-fitted element determined using the Gaussian least squares method. To facilitate the

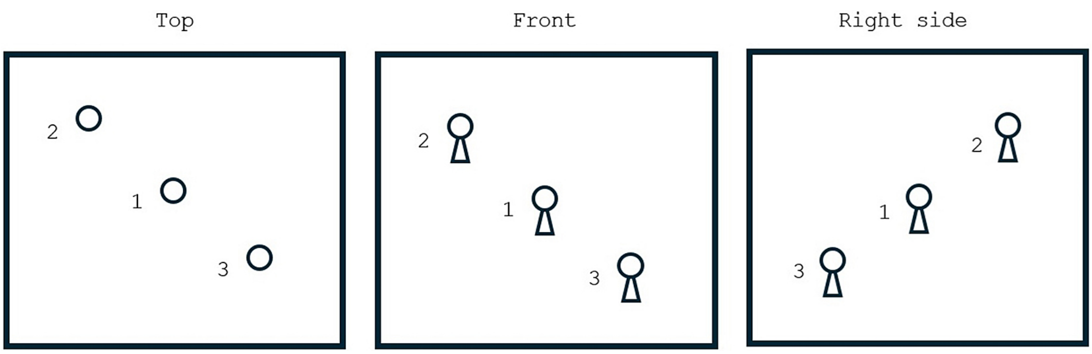

Figure 2. The possible locations of standard which can be used during verification of the combined operation of the point acquisition systems included in the HMS – left to right: top, front, right side view

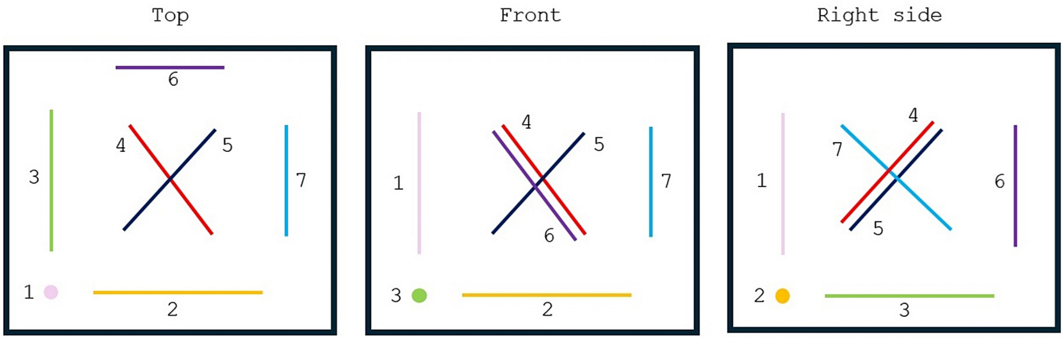

Figure 3. The possible locations of standard which can be utilized during verification of the length measurement error – left to right: top, front, right side view

straightforward application of the data fusion method, it is recommended to perform these tests simultaneously by mounting the ring gauge, which can be used as a reference element for the data fusion method, in close proximity to the flatness standard. This approach will also shorten the measurement time needed for application of developed procedure, as the measurements of the flatness standard and the ring gauge will be carried out simultaneously. The position and mutual orientation of the reference object and the utilized contactless measuring system in each of the test positions should be carefully chosen to ensure that the measurement encompasses the largest possible surface of the reference ring. The possible locations of standard which can be used for test described in this point are shown in Figure 4.

Uncertainty estimation

The assessment of the uncertainty of measurements of the reference objects required development of a detailed uncertainty budget for each of the performed tests. The basis for estimating individual uncertainty components is provided by the standards ISO/TS 17865:2016 [28], ISO/TS 23165:2006 [29], and ISO 14253-2:2011 [30]. The proposed equation for determining the uncertainty budget for form deviation measurements (roundness, flatness) takes the following form (2):

$$u(\varepsilon_{form}) = \sqrt{(\tfrac{F}{2})^2 + u^2(f) + u^2(\varepsilon_{RA}) + u^2(\varepsilon_{op})} \quad (2)$$

where: F – form deviation read from the calibration certificate of the standard, $u(f)$ – standard deviation of calibration of reference object, $u(\varepsilon_{RA})$ – standard deviation related with resolution of measuring system, $u(\varepsilon_{op})$ – standard deviation related with operator of measuring system.

The proposed Equation for determining the uncertainty budget for length and internal/external diameter measurements takes the form (3):

$$u(E) = \sqrt{\begin{array}{c} u^2(\varepsilon_{cal}) + u^2(\varepsilon_{\alpha}) + \\ + u^2(\varepsilon_t) + u^2(\varepsilon_{align}) + u^2(\varepsilon_{fixt}) + \\ + u^2(\varepsilon_{RA}) + u^2(\varepsilon_{op}) \end{array}} \quad (3)$$

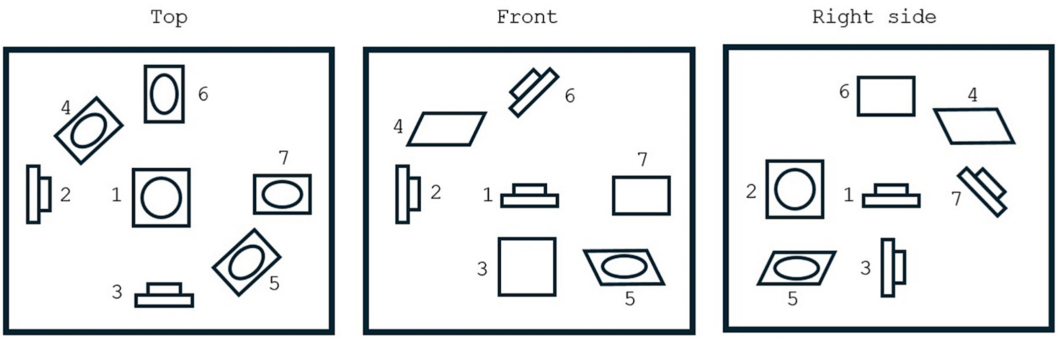

Figure 4. The possible locations of standard which can be utilized during verification of the error of flatness and roundness measurement – left to right: top, front, right side view

where: $u(\varepsilon_{cal})$ – standard uncertainty related with utilized lenght standard, $u(\varepsilon_{\alpha})$ – standard uncertainty related with determination of reference object thermal expansion coefficent, $u(\varepsilon_{t})$ – standard uncertainty related with reference object temperature, $u(\varepsilon_{align})$ – standard uncertainty related with reference object aligment, $u(\varepsilon_{fixt})$ – standard uncertainty related with method used for fixing reference object, $u(\varepsilon_{RA})$ – standard uncertainty related with resolution of measuring system, $u(\varepsilon_{op})$ – standard deviation related with operator of measuring system.

Additionally, for tests in which measurements are performed by both systems within the HMS, the uncertainty of measurements using each system individually must be assessed, and then the combined measurement uncertainty using the HMS should be evaluated according to Equation 4 or 5 (for form deviations or length/diameter measurements, respectively).

$$u_{HSP}(\varepsilon_{form}) = \sqrt{u_{tac}{}^{2}(\varepsilon_{form}) + u_{sca}{}^{2}(\varepsilon_{form})} \quad (4)$$

$$u_{HSP}(E) = \sqrt{u_{tac}{}^{2}(E) + u_{sca}{}^{2}(E)} \quad (5)$$

where: $u_{tac}(\varepsilon_{form})$ – standard uncertainty of form deviation measurements performed with tactile measuring system, $u_{sca}(\varepsilon_{form})$ – standard uncertainty of form deviation measurements performed with contactless measuring system, $u_{tac}(E)$ – standard uncertainty of length/diameter measurements performed with tactile measuring system, $u_{sca}(E)$ – standard uncertainty of length/diameter measurements performed with contactless measuring system.

RESULTS

Guidelines described in previous section were used to determine maximum permissible errors equations for developed HMS. Firstly probing systems of both devices that constitutes HMS was checked using spherical standard of 100 mm diameter. The results of measurements are shown in Table 3 which presents the biggest deviations obtained during experiments.

As can be observed all obtained results lie within MPE area specified for individual parts of HMS so it can be assumed that they work properly and rest of the tests can be proceeded.

Next the reference sphere was measured in three positions in measuring volume of HMS using developed data fusion method (described in last paragraph of section "the hybrid measuring system comprising large scale CMM and 3d scanner"). Table 4 shows the biggest differences in relation to values given in sphere calibration certificate obtained during measurements. The measurement process is shown in Figure 5.

It is clearly visible that for both parameters accuracy of HMS treated as w whole is slightly better than for structured light working as a separate device.

Table 3. Determined values of sphere diameter deviations and form deviations compared to MPE values stated for systems that constitute hybrid measuring system (HMS)

Feature/relation	Developed traceability assurance method		MPE value (given in calibration certificate of tested device)
	X, mm	U(x), mm	X, mm
Sphere diameter deviation (tactile measurement on CMM)	0.0006	0.0010	0.0018
Sphere form deviation (tactile measurement on CMM)	0.0018	0.0007	0.0022
Sphere diameter deviation (measured using structured light scanner)	0.0110	0.0123	0.025
Sphere form deviation (measured using structured light scanner)	0.0216	0.0193	0.045

Table 4. Determined values of sphere diameter and form deviations compared to values from calibration certificate of reference element

Feature/Relation	Developed traceability assurance method		Value from calibration certificate of standard	
	X, mm	U(x), mm	X, mm	U(x), mm
Sphere diameter	101.5794	0.0096	101.5888	0.0007
Sphere form deviation	0.0193	0.0171	0.0027	0.0010

Figure 5. Measurements of reference sphere during tests on combined accuracy of hybrid measuring system (HMS) probing systems

Third test is aimed at determination of length measurement error of HMS. The ball-bar standard was used for this test with balls spaced every 100 mm. The longest possible distance of 3000 mm was selected for measurements. Ball-bar standard is shown in Figure 6. The biggest obtained difference between measurement result and nominal value given in certificate is shown in Table 5.

The last test included in traceability assurance method for HMS was conducted using flatness standard and ring gauge. Results of performed measurements are presented in Table 6. Again the biggest difference between measurement results and value given in calibration certificate of

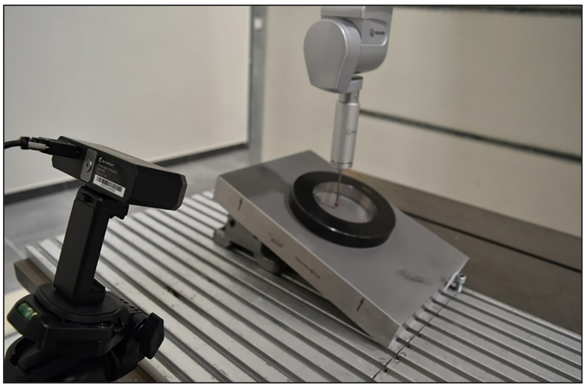

Figure 7. Measurements of flatness standard and ring gauge in one of seven positions in HMS measurement volume

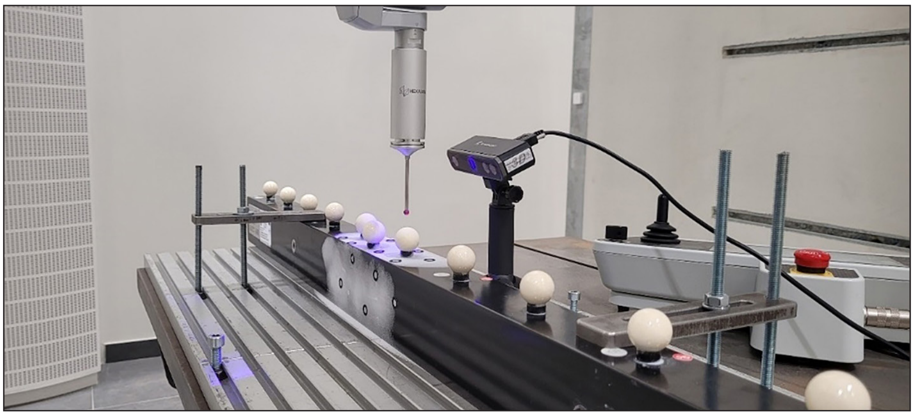

Figure 6. Determination of common coordinate system for HMS on ball-bar standard

Table 5. Measured values of 3000 mm length reproduced by ball bar standard compared to value from calibration certificate of standard

Feature/Relation	Developed traceability assurance method		Value from calibration certificate of standard	
	X, mm	U(x), mm	X, mm	U(x), mm
Distance between spheres no. 0 and 30 of 3 – metre-ball-bar standard	2999,2546	0.0091	2999,2479	0.0021

Table 6. Determined values of flatness and roundness deviations compared to values from calibration certificate of standards

Feature/Relation	Developed traceability assurance method		Value from calibration certificate of standard	
	X, mm	U(x), mm	X, mm	U(x), mm
Flatness deviation	0.0077	0.0058	0.0026	0.0015
Roundness deviation (for standard ring)	0.0112	0.0108	0.0003	0.0002

Table 7. Determined values of sphere diameter deviations and form deviations compared to MPE values stated for systems that constitute hybrid measuring system

Task	Task-specific MPE value, mm
Sphere diameter measurement	0.020
Sphere form deviation measurement	0.037
Length measurement	0.016
Flatness measurement deviation	0.014
Roundness deviation	0.023

standard is shown. The measurement process is shown in Figure 7. Basing on the obtained results of all performed measurements it is possible to formulate MPE limits for HMS taking into consideration different measurement tasks. All obtained MPE values are summarized in Table 7.

CONCLUSIONS

Traceability assurance method for measurements performed using hybrid measuring systems developed within works presented in this paper have two main tasks. At first, it should be used for providing traceability of results obtained using HMS to unit of length, meter. It is done by performing measurements of material standards that were calibrated in accredited calibration laboratories or laboratories run by National Metrology Institutes. Second task of developed method, that is related to the first one, and may be achieved by pursuing the same experimental methodology, is determination of values of task-specific maximum permissible errors. There is also at least one more advantage of this method. By running measurements described as test 1 in subsection "Method for ensuring traceability of Hybrid Measuring System" the user of a HMS may obtain answer to the question if both systems (tactile one and optical one) constituting HMS are working properly and within MPE ranges specified for them. So this test is some kind of measuring system self-diagnostics.

Results presented in previous section shows that HMS developed in this paper is capable of performing measurements traceable to unit of meter. As can be observed in Tables 4–6 intervals presenting material standard calibration value plus/minus calibration uncertainty values in all cases intersects with intervals created as value determined using developed traceability assurance method plus/minus uncertainty associated to it. Basing on this, it may be concluded that the real value of the feature/relation that is searched during measurement lays in the intersection zone of mentioned intervals and measurements performed using HMS are traceable to material standards calibration results. What is more, the maximum permissible errors related to different measuring tasks that may be solved using HMS were determined. It may be observed that considered HMS has the biggest value of MPE for sphere form deviation measurement, which it is equal to 0.037 mm. The smallest value of MPE was obtained for measurement of flatness deviation (0.014 mm) and length measurement (0.016 mm). This kind of error characteristics may be attributed to optical system included in the HMS, which in fact, as the less accurate system, decides on the measurement accuracy of the whole HMS. Results presented in Table 3 gives clear information that both systems that constitutes the HMS are working correctly and providing values below MPE values stated separately for them.

In authors opinion, the most important advantage of developed method is possibility of determining the task-specific MPE values. As a task-specific uncertainty is the well-known idea, up to date there were not many attempts to describe also maximum permissible errors as task-specific values. For coordinate measuring systems (CMS), MPE values are usually determined for length measurement errors and form, size, location measurement errors determined for spherical or circular standards. Utilizing this approach, user of CMS cannot say what level of error he may obtain, for example for measurements of squareness, parallelism or coaxiality deviations? Determination of MPE values separately for different tasks known from geometrical dimensioning and tolerancing framework fix this problem and simplify process of proper measuring tool selection for different measuring tasks defined with assumed tolerance zones (which is related to use of golden rule of metrology).

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