Verification of Computed Tomograph for Dimensional Measurements

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Abstract. Radiation, is one of the ways of energy transfer by emission of electromagnetic waves or particles from a radioactive source. X-ray images make it possible to observe the internal structure of virtually any object and the only limitation is the ability to overexpose it. Tomography is a technique that allows imaging on the basis of sections or cross-sections obtained by means of a wave penetrating the object. The devices used in X-ray computed tomography consist of four basic components: the X-ray tube, the detector, the manipulator, and shielding to protect against the negative effects of X-rays on the operator. Measurements of geometric quantities carried out with a CT scanner are classified as coordinate measurements, and they are subject to the same conditions as, for example, contact or optical measurements carried out with other coordinate systems. Since that, the methods of its verification are derived from the methods applied to other devices operating in this technique. In the paper a metrological approach to computed tomography from verification and reverification point of view was presented. Documents related to it were briefly described and a practical example of inspection performed with standards was presented.

Keywords: Computed tomography · Verification · Standard

1 Introduction

Since the dawn of time, man has been trying to learn more about himself and the world around him. This desire is a mechanism of continuous development causing progress in all areas of life. Practically in every such case an indispensable "tool" is metrology in its broadest sense, giving the possibility of reliable description of reality with the help of definitions and units that are specific to it. Each correctly conducted measurement allows for confirmation or negation of the validity of theses and classification of phenomena or assessed objects. For centuries, in the field of metrology of geometric quantities, measurements could be divided into two main groups: contact measurements - that is, measurements where physical contact with the test object takes place, and non-contact

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measurements, where this contact does not occur. The results obtained by different techniques are not always consistent with each other [1]. In non-contact measurements, the most widely represented group are optical measurements. Apart from many advantages, their certain disadvantage is the necessity to observe the measured object, which excludes, for example, the evaluation of internal inaccessible closed spaces. In such a situation, the only solution some years ago was the necessity to destroy the tested object and the measurement, based on specially prepared sections.

Radiation, is one of the ways of energy transfer by emission of electromagnetic waves or particles from a radioactive source. One of the special features is that there is no need for a material medium between the source of emission and the receiver [2]. Taking into account the above arguments it can be stated that radiation penetrating the matter and enabling observation of internal structure of objects described by Wilhelm Röntgen was a breakthrough discovery. X-ray images make it possible to observe the internal structure of virtually any object and the only limitation is the ability to overexpose it. Thus, electromagnetic radiation can be used in metrology not only in the visible range [3]. X-rays discovered by Röntgen are electromagnetic waves [4]. The wavelength is assumed to be in the range $10^{-12} \div 10^{-8}$ m and can be further divided into more penetrating hard radiation ($10^{-12} \div 10^{-10}$ m) and less penetrating soft radiation ($10^{-10} \div 10^{-8}$ m). However, the boundaries set by wavelength are not sharp and in some areas the wavelength of X-rays overlaps with gamma rays.

X-rays - in addition to medical applications have also become important in technical sciences. They allow not only to find pores and identify different materials, but also to measure dimensions. However, in order to reproduce the measure correctly in this respect, metrological verification of the tomographs is necessary. Therefore, the paper presents steps in this direction and examples of activities-based.

2 Computed Tomography

In general, tomography is a technique that allows imaging on the basis of sections or cross-sections obtained by means of a wave penetrating the object. The image resulting from the measurement is obtained as an effect of reconstruction resulting from mathematical calculations. Tomography is used in all areas of science and life, and the choice of wave source depends on the application and safety conditions.

One of the best known varieties of tomography is X-ray based computed tomography (CT) or more precisely known as x-ray CT [5]. Its first application was related to medicine, however, it is gradually paving its way for application in technology and is increasingly used not only for defect analysis but also for measurements of geometrical features [6]. Computed tomography is called X-ray tomography in medical applications [7, 8]. In contrast, technical tomographs are often called microtomographs (micro-CTs), as they allow imaging with a resolution even below a micrometer. Since they are not designed for the study of living organisms, it is possible to increase the exposure time to X-rays by increasing the number of images, increasing the recording time, and the power of the X-ray tube. Micro-CTs are also used in medical and biological measurements when images with adequate resolution are sought [9, 10].

In X-ray CT measurement, the radiation beam is attenuated as it passes through the object, and this process depends on the thickness of the absorbing medium and the absorption coefficient related to the same length units. During the measurement, a number (usually hundreds or thousands) of 2D X-ray images are taken for different angular positions of the lamp-detector system relative to the measured object [11]. As a result of reconstruction from 2D shots, a spatial image is obtained. X-ray tomography is classified as non-destructive testing. However, one should always remember about the negative influence of X-rays on living organisms.

Of the tomographic techniques, X-ray computed tomography is the most widely used worldwide [12]. Allan MacLeod Cormack and Godfrey Newbold Hounsfield are considered to be its creators. The devices used in the technique are characterized by better resolutions and/or higher powers of radiation sources [13]. They consist of four basic components: the X-ray tube, the detector, the manipulator, and shielding to protect against the negative effects of X-rays on the operator. In a more automated version, the tomograph can also be equipped with a robot that feeds and receives objects for measurement, as shown in Fig. 1.

Fig. 1. Schematic image of the tomograph with the supply robot [14].

Since the beginning of CT as the youngest branch of coordinate measurement technology, attempts have been made to determine the parameters characterizing the performance of these devices from the point of view of accuracy features [15]. X-ray techniques previously used exclusively for the analysis of defects and flaws were limited to quality functions (good/bad) and the assessment of the object as in accordance with the requirements (flaws - if they could be detected, they are small enough not to disqualify the object) or not (defects occurred that are large enough to make the object unusable). This assessment was very often made by an operator, rarely supported by decision-making software, having a possibility of comparing a defect found in an object to a defect classified in a limit defects catalog. The development of tomographic techniques has allowed their use for both evaluation and measurement in a wide variety of fields, including metal components [16], plastics [17], foams [18], and even building components [19]. They have also become an important tool for verification of work in reverse engineering [20] and in the multi-criteria evaluation of components made by incremental techniques.

Measurements of geometric quantities carried out with a CT scanner are classified as coordinate measurements, and they are subject to the same conditions as, for example, contact or optical measurements carried out with other coordinate systems [21]. Similar conditions apply from ISO 17025 point of view, which concerns accredited testing and calibration laboratories.

3 Errors and Different Concepts of CT Verification

Since the technical tomograph is a device operating as a coordinate measurement system (CMS), in a natural way, the methods of its verification are derived from the methods applied to other devices operating in this technique. In this respect, the basic functionality of the tomograph covers the macro scale, although there are situations in which it can also be used for analyses on the micro scale [22, 23], as well as for data preparation for surface modelling [24]. The essential standard in this field describing methods for checking coordinate measuring systems in the macro scale is ISO 10360, whose individual parts concern, among others, verification of contact coordinate measuring machines [25], optical devices [26, 27], laser trackers [28], or articulated arms [29]. A part of standard for computed tomographs is currently in preparation and this part will have the number 11. But until it is published, the basic document describing the operation and metrological verification of a technical computed tomograph is the German recommendation VDI/VDE 2630.

The four parts of this elaboration [30–33] comprehensively discuss issues related to the design, capabilities, and accuracy characteristics of computer tomographs used for geometric analysis. This document was prepared by the German industry, which first saw in tomographs the opportunity to realize even more thorough dimensional inspection of objects and assembly groups, thanks to the active Association of German Engineers (VDI) and the Association of Electrical, Electronic and Computer Engineering (VDE). Its primary purpose is to define conditions and methods to ensure the comparability and traceability of measurement results performed with CT. This document was created in 2009–2010 and, as already mentioned, until now it is the only one addressing so comprehensively the issues presented above. Despite the passage of almost ten years, during which individual elements of CT scanners have developed, sometimes very dynamically, this study has not lost its relevance.

A number of factors influence the reliability of tomographic measurements. They can be divided according to their source, so we distinguish between factors related to the device itself (tomograph), the measurement task, the analysis procedure, as well as the environmental conditions and the operator. Among the factors related to the measurement device, we can further distinguish between factors originating from different elements of the tomograph. Those related to the X-ray tube, i.e. the radiation source, are primarily voltage and current and their stability over time, as well as the size and shape of the spot in focus, its position and stability, the material used for the material filters and their thickness, and any kind of abnormal beam propagation. The factors that cause inaccuracies related to lamp performance refer to drifts, namely, focus drift, lamp output drift, and temperature drift. Linear and rotational axis inaccuracies are another component of the device that affects its reliability. These include the orientation of the rotary axes, the perpendicularity of the source axis and the detector plane, interference from control and heating, and static and dynamic guidance errors of the linear and rotary axes.

The detector and the errors associated with it are also a very important element affecting the accuracy parameters of the CT scanner. There are a lot of different influencing factors, the most significant of which are internal scattered radiation, filter, cooling, pixel size and number of pixels (including errors), grey scale resolution, exposure time, stability, and even operating mode. When analyzing a CT scanner, one must also not forget about its environment and the changes that occur within it. Ambient conditions have such an impact as on any length measurement regardless of the measurement system used and refer not only to temperature and humidity, but also to vibrations and contamination in the air during the measurement and the influence of scattered radiation. On the side of the measurement task, the accuracy characteristics are of course influenced by the object itself and the measurement conditions, i.e. the parameters set on the tomograph. The object is characterized by both geometry (shape) and material data (ease of radiation penetration through the object), and influencing factors further include mounting, angular position, scattering and radiation hardening. On the other hand, pre-filtration, number of angular positions and vertical resolution, magnification and object position are among the important conditions. The analysis procedure, i.e., the capabilities and operation of the reconstruction software, as well as the data analysis related to the voxel size, are also crucial for the tomographic accuracy parameters and measurement uncertainty. Here we distinguish between voxel and surface data reduction, surface extraction, as well as object basing and the functioning of algorithms for reconstruction, correction and analysis. The last group of influencing factors are those resulting from the operator's work, i.e. the selection of the measurement strategy (resulting from the specific measurement task) and its implementation and experience, especially important in the case of items made of materials of very different densities and complex shapes. In addition, many of the factors described above influence not only the measurement uncertainty itself, but also other factors, resulting in complex relationships and the occurrence of dependent variables.

The standardization approach and the idea of creating a standard for the verification of tomographs as part of ISO 10360 includes - also from a standardization point of view - computer tomographs into the group of coordinate measuring systems and unifies the metrological approach to the verification of the functioning of these systems. The tomograph will thus be able to be a stand-alone measurement system, but it will also be able to be part of a multi-sensor system [34], and its errors will be governed by the relevant normative provisions. Treating the verification of these devices as part of ISO 10360 also makes it possible and necessary to use terms generally accepted throughout the standard. Part 11 of the ISO standard is therefore intended to give the definitions of the metrological characteristics and methods of their verification for coordinate measuring systems using the principle of computed tomography intended for the measurement of technical objects and appearing as a single-sensor device (if the system has two tubes it is treated like two lenses in optical coordinate measuring machines or two sets of lenses for different measuring fields for optical coordinate measuring scanners). The listing of technical subjects is intended to separate tomographs for industrial use from medical imaging and measuring devices and from tomographic material applications (e.g., defect analysis). Many standardization ideas related to standards are based on previous research work [35, 36]. The characteristics likely to be found in this part of the standard will therefore allow the specification of the parameters of coordinate measuring systems using the principle of computed tomography (attenuation of the signal when passing through material elements of different density) and any related comparisons. This applies to both planar and conical beam measuring systems, as well as systems collecting data along a spiral, which are considered by some to be the future of dimensional control, for example in the analysis of the wall thickness of castings. It is further assumed that the standards used for verification of CT-based coordinate measuring systems will be homogeneous (without obvious gradients in X-ray attenuation) and made of uniform materials. In addition, the effect of surface irregularities is determined to be negligible and not the subject of this part of the standard. However, it can also be applied to other CT systems, after appropriate adaptation and mutual acceptance (supplier/customer). Thus, the introduced standard addresses length and sampling errors. Additional aspects in the calibration of the systems described therein are expressed, among others, in the use of alternative length standards to gauge blocks and the comparability of features when using these standards, and the comparability of features when using different measurement strategies. It also introduces the term “artifact” as an error in an image being a consequence of the use of the term in the field of computed tomography. Errors that verify CT performance can be unidirectional and bidirectional. As elsewhere in the standard, any error should be less than the maximum allowable error. Maximum allowable values are generally provided by the coordinate measurement system manufacturer. This is always the case for new systems; if it is a reverification, the user can specify different values. Verification and reverification tests can also be carried out with a load on the load cell of the maximum mass allowed for a particular system. The manufacturer can also specify a maximum table load, expressed per unit area. In addition, the measurement time is important in the verification of CT systems and should be specified after verification. The manufacturer should specify a maximum time for the test and optionally also a minimum time.

4 Research Setup

A practical way of verifying the basic accuracy parameters of a CT scanner was realized by means of sample standards. A Waygate Technologies v|tome|x s 240 CT scanner equipped with two 240 kV/320 W microfocus and 180 kV/15 W nanofocus X-ray tubes was selected for the study. A temperature stabilized DXR 250RT detector array with 20 fps for real-time inspection, 200 μm pixel size, 1000 × 1000 pixels on a 200 mm × 200 mm large active area with 2x virtual detector enlargement was used to capture the X-ray images. It enables measurements of components made of both plastics and metals. As the CT scanner is classified as a coordinate measuring system, it was decided to carry out tests on a dedicated ball-bar type gauge with a sphere diameter of 5 mm and centre distance of 39.9715 ± 0.0010 mm. These two ruby spheres have the same nominal diameter. However, during the CT scan, one of them (sphere 1 at the top) is visible all the time, while sphere 2 (at the bottom) is sometimes obscured by the rod (pin). This situation may affect the obtained results. The second measurement cycle was to test gauge blocks with nominal sizes of 1, 5, 10 and 20 mm (Fig. 2). Gauge blocks are commonly used for dimensional inspection of CMMs, among others, so their use in this case is an analogy between CT and CMS.

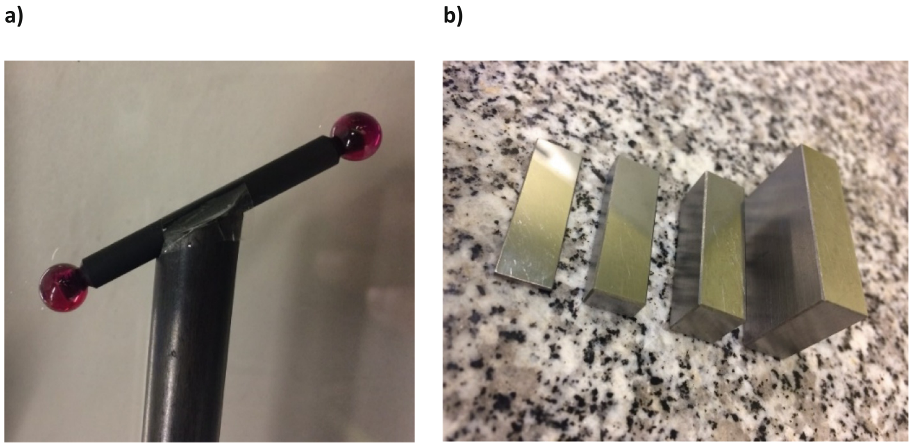

Fig. 2. Test standards used in the study: a) Ball-bar, b) 1, 5, 10 and 20 mm gauge blocks.

As the measured object moves away from the x-ray tube toward the detector, the magnification decreases. The ball-bar pattern was measured at three positions. In the first case, the standard was examined for the maximum possible position corresponding to the situation in which the object occupies the entire available detector space. This corresponds to a voxel size of 43.993 µm. The second position corresponded to the lowest possible magnification (for a feature distance of 500 mm from the lamp) and in this case the voxel has a size of 123.007 µm. The third position corresponded to the middle position between the two extremes, and the voxel size was 83.616 µm. In each case, measurements were made with a current of 190 µA, a voltage of 170 kV, and an exposure time of 200 ms for a single image. For each position, the measurement was performed with a different number of measurement images (1500, 1000, 800, 600, 400, 200, 100 images) uniformly distributed over a full rotation of the sample. The measurement for each condition was repeated 10 times.

In the second study, gauge blocks were evaluated. All elements were measured for the same X-ray tube parameters, i.e., 220 kV voltage and 245 µA current. The magnification was 5.099, which corresponds to a voxel size of 39.221 µm. For each gauge block, 1000 measurement shots were taken and each measurement was again repeated 10 times.

5 Results and Discussion

5.1 Ball-Bar Measurements

For each standard measured according to the procedure given, the diameter and sphericity of each of two spheres with a nominal diameter of 5 mm was determined. In addition, the distance between the centres of the reference spheres was calculated. Figure 3 shows the results for the diameter measurement of spheres 1 and 2.

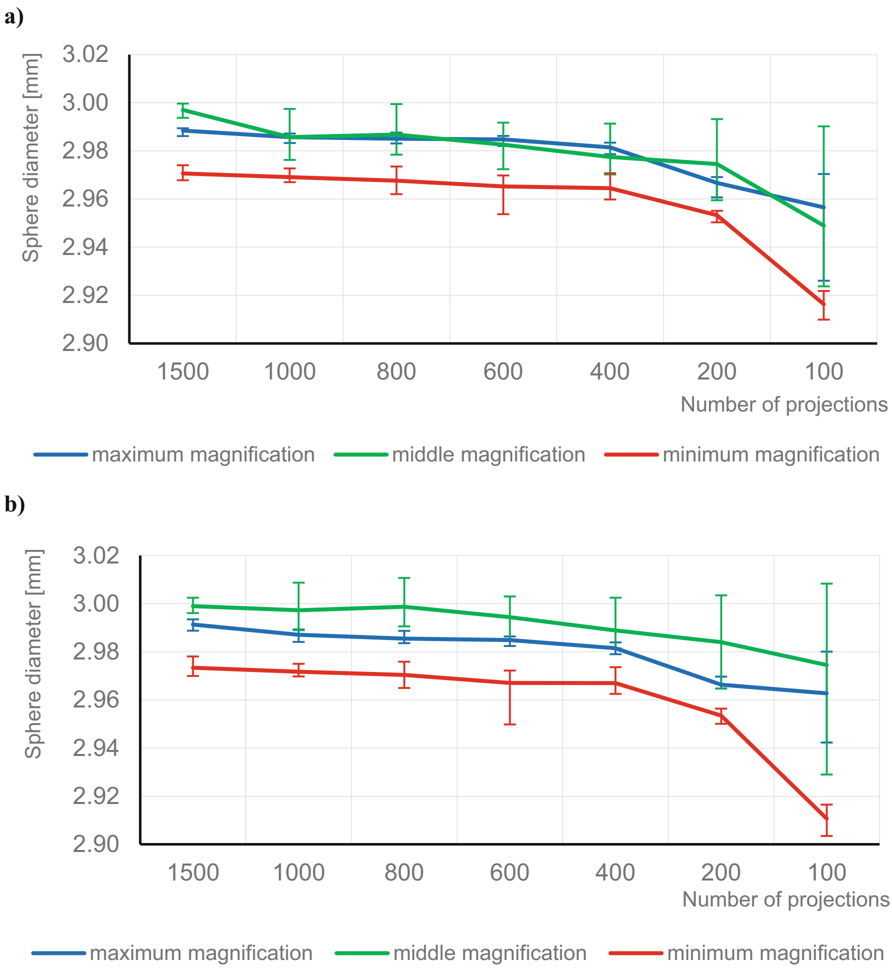

Fig. 3. Results of diameter measurement: a) sphere 1; b) sphere 2.

Analyzing the data presented in Fig. 3 it can be stated that in both cases the spheres measured with the lowest magnification are also characterized by the lowest diameter value. Also for those spheres the decrease of the diameter is most distinct, which is correlated with the reduction of the number of measurement images. The range of the diameter values for the individual number of shots is similar and reaches about 0.005 mm. The smallest values of the range can be observed for spheres measured with the maximum magnification, while the largest values were recorded for measurements with a small number of measurement images. It should be added here that 100 or even 200 shots are very small numbers and in practice may give far insufficient information about the measured object. In all cases the influence of the rod is not visible.

Figure 4 shows the shape deviation (sphericity) values for both measured reference spheres. In this case, some stability can be observed in the shape deviation results, for the standard measured with maximum and minimum magnification. This occurs in the range of 1500–600 measurement images. For the medium magnification there is a sharp increase in the shape deviation value between 1500 and 100 shots. Then its stabilization is observed up to 600 measurement images. In each of the measurement variants at the number of 400 images and less there is a sharp increase in the sphericity error resulting from less and less accurate reproduction of the shape of the reference spheres.

a)

b)

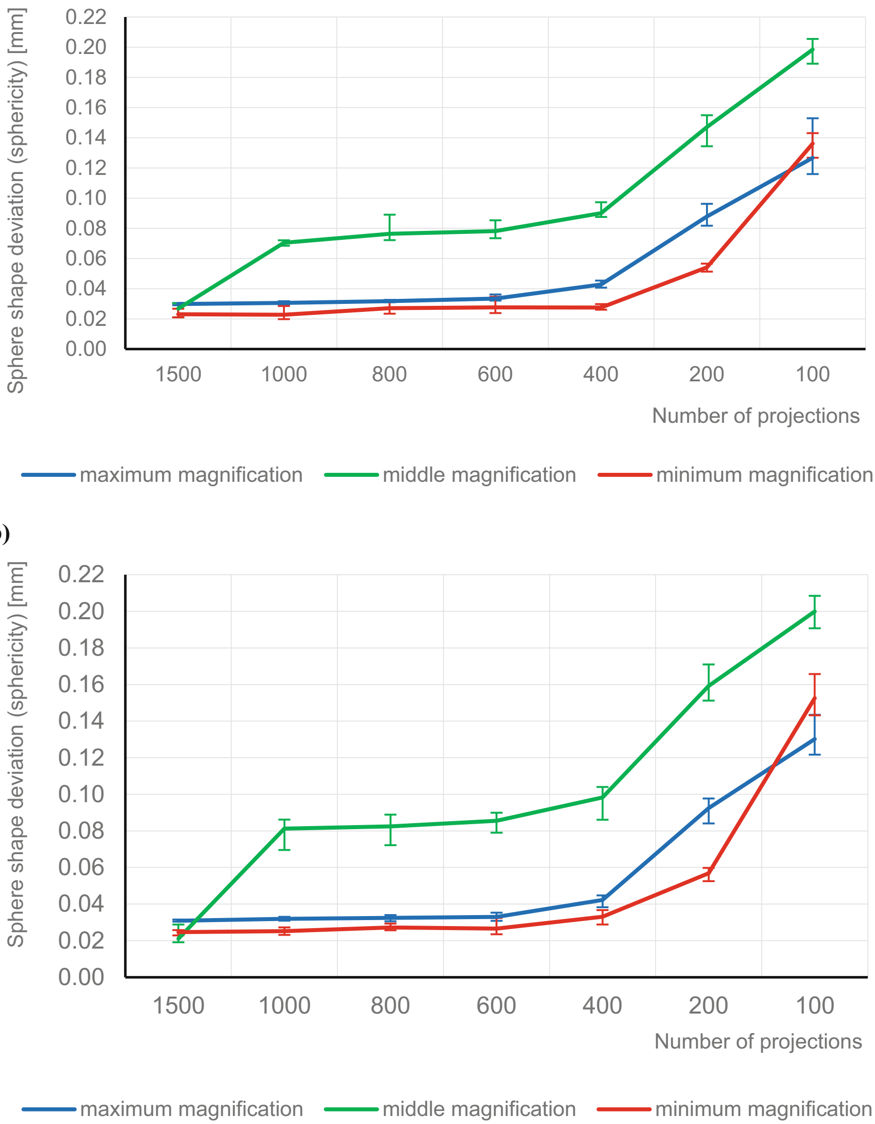

Fig. 4. Results of form measurement: a) sphere 1; b) sphere 2.

The last parameter that was determined for the ball-bar was the distance between the centres of its spheres. The results are shown in Fig. 5. Analyzing the data presented on the graph it can be observed that the difference of the average dimension in relation to the real value does not exceed ±0.005 mm in the range of 1500-400 measuring images. In the case of 200 and 100 images these values change significantly, which confirms that measurement with such a small number of projections can lead to erroneous information. When measuring the standard for the average magnification value, significant deviations in the obtained measurement results were observed. Sphericity is similar for both spheres - the measurement parameters were chosen correctly and the influence of the rod is not noticeable.

Tests conducted for a ball-bar type standard demonstrate its usefulness in the evaluation of CT scanner accuracy. What is important, such a construction of the standard allows to obtain a very wide range of standards in terms of dimensions, allowing verification of devices with different measurement ranges.

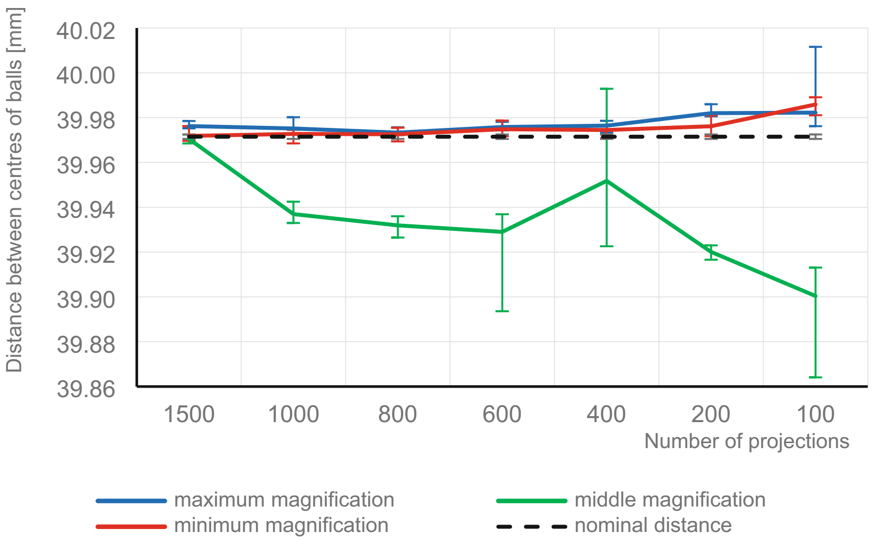

Fig. 5. Results of measurements of the distance between the centres of the ball-bar spheres.

5.2 Measurements of the Gauge Blocks

According to the methodology presented in chapter 4, gauge blocks with lengths of 1, 5, 10 and 20 mm were evaluated. The centre length of the gauge block was calculated, and the results are shown in Fig. 6.

Analyzing the obtained results, a strong increase in the dimensional difference can be observed as the length of the gauge block increases. This is due to the difficulty of penetration of "thick" gauge blocks by X-rays. During the passage through the measured object, there is a strong attenuation of the beam and an increase in the beam hardening

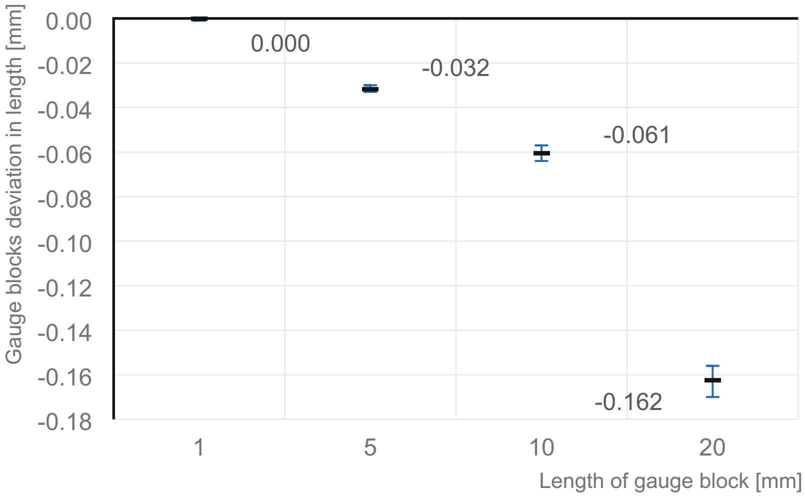

Fig. 6. Results of gauge blocks measurements.

phenomenon. This clearly shows that the use of gauge blocks to evaluate the accuracy of CT scanners is not proper and standards that do not cause such a significant obstruction during X-raying should be used.

6 Conclusions

From a verification and reverification point of view, it seems interesting to approach tomography as a single type of measurement and to be able to combine the results obtained by this technique with other coordinate methods, both optical and contact. In this way, it is possible to achieve smaller measurement uncertainty in areas where it is of particular interest, and to obtain a full set of coordinates (with larger uncertainty) in the rest of the measured object. This type of data fusion is possible not only at the macro scale, but also between scales, using macro-scale tomography and micro- or meso-scale surface roughness analysis techniques. Solutions combining traditional contact CMM and optical techniques and tomography in a single measuring device are also possible.

In this case the verification and reverification of the accurate functioning of the device requires the use of the guidelines of the already mentioned part 9 of ISO 10360. This standard distinguishes certain errors of a device or multisensor assembly, the systematics of which are similar to those used in its other parts. When analyzing the performance of multisensor assemblies, it has to be taken into account that not every software installed on a measuring system may have all the functions necessary to determine the geometric elements resulting from the definition of individual errors. In such a case, one can use a substitute evaluation or make an evaluation in external software.

Metrological approach to computed tomography allows fully reliable application of these devices for metrological analyses related to length and angle, and to some extent also to topography parameters in micro scale. Computed tomography also allows for the evaluation of surface irregularities in the way which is unattainable for other devices, as it makes it possible to assess reentrant features on the surface of printed elements made of sintered metal powders [37]. The influence of temperature on the measurement results is also very important with tomography, as in other parts related to coordinate techniques on a macro and micro scale [38]. This is especially important considering the multitude and variety of tasks that tomographs face. Looking into the future, the development of this measurement technology will further increase its application possibilities and it can be assumed with high probability that this technique should be expected to develop in the future similar to computed tomography in medicine.

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