Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 69 (2014) 255 – 262
Procedia Engineering
www.elsevier.com/locate/procedia

24th DAAAM International Symposium on Intelligent Manufacturing and Automation, 2013

Comparison of Different Method of Measurement Geometry using CMM, Optical Scanner and Computed Tomography 3D

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Abstract

Never-ending evolution of market expectations leads to new solutions in quality control. Nowadays, in most cases control of geometry in industry is carried out using devices that apply coordinate measuring technique. Since couple of years metrological computed tomography X-ray 3D has became on a market. It is the latest field of coordinate measuring technique what makes many aspects of its accuracy and possible applications still open. The paper presents information on the functioning and measurement using computed tomography X -ray 3D.
Results of comparative tests carried out on a coordinate measuring machine (CMM), optical scanner , and metrology computed tomography X -ray 3D are presented. The results allow us to conclude that computed tomography makes it possible to obtain comparable results with CMM and the optical scanner. Conducted investigations show areas where the use of the devices is appropriate and those in which the device is not adequate. In the case of X- ray 3D CT considerable versatility is presented which allow to describe the measured part with a cloud of points. Obtained information has an equal density of the part exterior and interior. This allows to reliably assess the test characteristics. The difference in presented results do not exceed 0.05 mm. One of the reasons for them is the method of measurement - for CMM tactile measurement causes information gap between the data points. In the case of the optical scanner is difficult to collect data points in holes of small diameter , what causes errors in the assessment of the position and diameter. For the CT, a significant reduction in the absorption of X-rays , which translates into an actual measurement volume and the occurrence of artefacts. The paper shows the effect of different research methods on the obtained results and their application areas. This information can help a potential user to select the appropriate measuring device.

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Keywords: 3D computed tomography; X-ray CT; coordinate metrology; accuracy of measurement

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doi:10.1016/j.proeng.2014.02.230

1. Introduction

Coordinate measuring technique is the field of metrology of geometrical quantities, which is rapidly developing at present. A wide range of methods can be rated to this technique on account of the essence of the measurement - collection of the coordinates describing a position of the individual measuring points. The range starts from relatively simple methods such as diameter measurement with the use of a microscope, through coordinate machines and optical scanners and ends on single-purpose devices such as formtesters. Measurement of roughness or large size objects with the use of laser tracker can be counted to the coordinate measurement. A common feature of the above-mentioned methods is the possibility of estimation of the surface only - the surface which can be seen or touched by a gauging point.

Computed tomography (CT) has recently allowed to extend the measuring possibilities. This method uses X-raying the objects. CT scanners are known in medicine for a long time, but for technical imaging of 3D objects, these devices have been used for 10 years. The image from CT scanner allows for estimation of the geometry of manufactured product as well as internal closed surfaces. It also allows for analysis of pores in material interior or estimation of subassemblies deformation during joining [1, 2].

2. Basic principle of X-ray techniques

X-ray tomography is a class of radiological examination techniques where X-ray tube motion is a common feature [3, 4, 5 ,6]. This motion allows to obtain a clear image of internal structure of the examined object. The word "tomography" is derived from the Greek: tomos (slice) and graphia (to write). In 1962, this name was accepted by the International Commission on Radiologic Units and Measurements for determining all radiographic techniques which make tomograms [7]. Computed tomography is a type of X-ray tomography - the method that allows for obtaining tomographic images (slices) of the examined object [8, 9]. The discovery of X-rays was done by W.C. Röntgen in Würzburg in 1895. The first X-ray image showed his wife's hand (Fig. 1).

Fig. 1. First X-ray image.

Tomography is based on a theorem of an Austrian mathematician, Johann Radon, who proved in 1917 that 2D and 3D image of an object can be completely reconstructed from the infinite number of projections of the object [10, 11].

When X-raying the measured object, a part of radiation is absorbed with different rate by different materials. The higher the material density, the higher the absorption of radiation. The material density is connected with the atomic number. Hence, a lead, for example, with the atomic number of 82 is used as a radiation shield in order to protect from X-raying. Steel objects (Fe 26) absorb X-rays more than aluminum (Al 13).

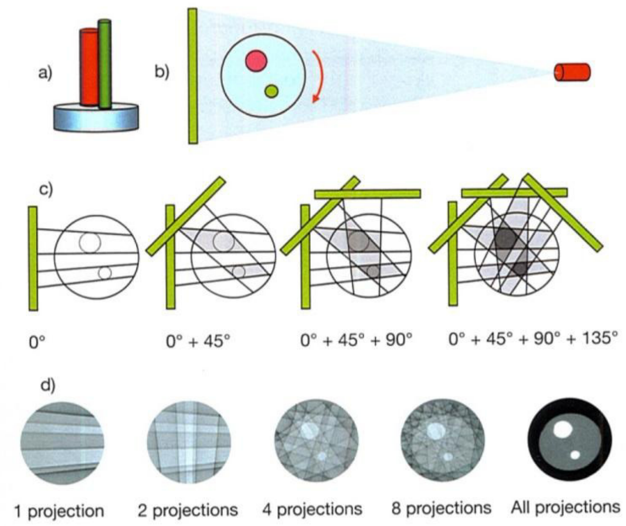

Fig. 2. Calculating volume data by back projection of filtered radiographic images: a) Object, b) X-ray beam path in one section plane, c) Principle of stepwise back projection and superimposing, d) Results of reconstruction with different numbers of back projections for a real workpiece [12].

3. Construction and operation of CT

First CT system was elaborated by Hounsfield and Cormack in years 1969 – 1972. Its production started in 1973. First commercial X-ray tube was designed by W.D. Coolidge in 1913 [13]. He applied tungsten filament heating in order to form the electron beam in a glass tube with vacuum (Fig. 3).

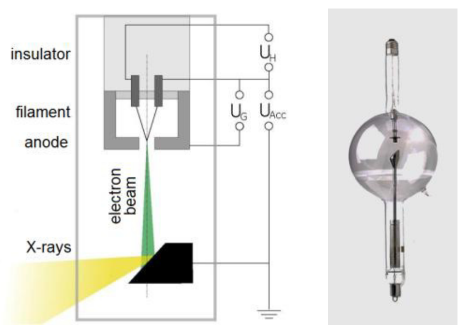

Fig. 3. First commercial X-ray tube.

Nowadays, two types of tubes are used in CT systems for the measurement of mechanical parts, i.e. transmission and reflection tubes. Transmission tube allows for obtaining a higher magnification and reflection tube allows for higher power.

In order to get a higher resolution of CT, microfocus and nanofocus tubes are used (Fig. 4). Nanofocus tubes are additionally equipped with a diaphragm which allows for obtaining a spot with very small size - even below the value of one micrometer.

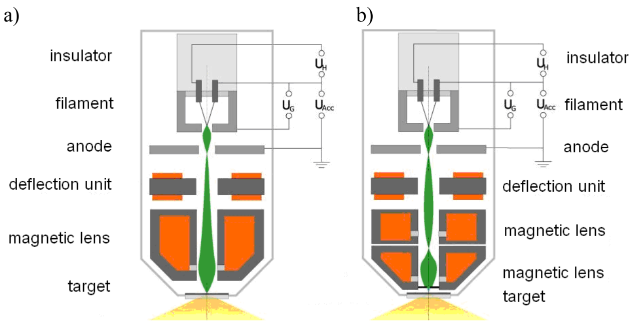

Fig. 4. Tubes applied in CT scanners: a) microfocus, b) nanofocus [14].

CT systems are designed as 2D and 3D versions. 2D CT scanner is called a CT with planar fan beam, and 3D CT scanner is called a CT with cone beam (Fig. 5).

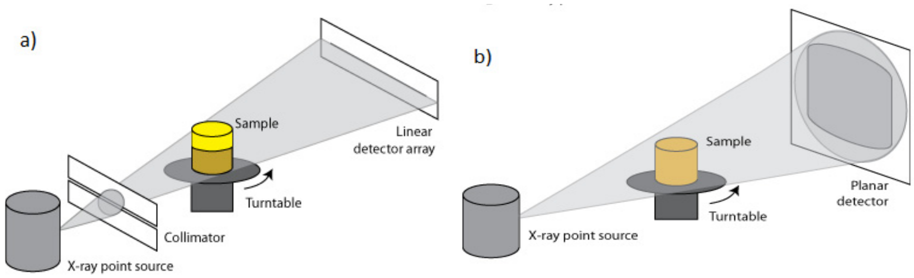

Fig. 5. CT systems: a) with planar fan beam, b) with cone beam [15].

The next important element of CT system is a detector, i.e. a system that presents the obtained image. At first X-rays are changed into a visible light by film or scintillation crystal and then the visible light is received by photodiodes and these ones allows for presentation of the image.

4. Coordinate measurements with the use of CT

Coordinate measuring technique is still developing. Microscopes and contour projectors were the first devices which allowed to measure in 2D system. First coordinate measuring machines appeared on a market at the beginning of 1960s. Next measuring arms and optical scanners entered the market. Commercial metrological CT appeared in the first years of the 21st century.

In all above-mentioned devices the measurement is done by detection of the measuring point coordinates describing the examined object. The obtained data are digitally processed and this allows to obtain an information on the actual dimensions or form and position deviations. Except for an information on the surface, in case of CT we can get an information on the internal section as well. This allows to detect pores or estimate the geometry of closed surfaces.

Making the tomographic image consists in the measurement of radiation absorption which penetrates the object. The object volume is divided into small cells - called voxels which have the same linear coefficient of radiation absorption. The reconstructed sectional image is a quantitative map of the linear coefficient of radiation absorption in voxels which are a part of the scanned slice [16, 17, 18]. The obtained cloud of points allows to conduct the analysis of dimensions and internal structure.

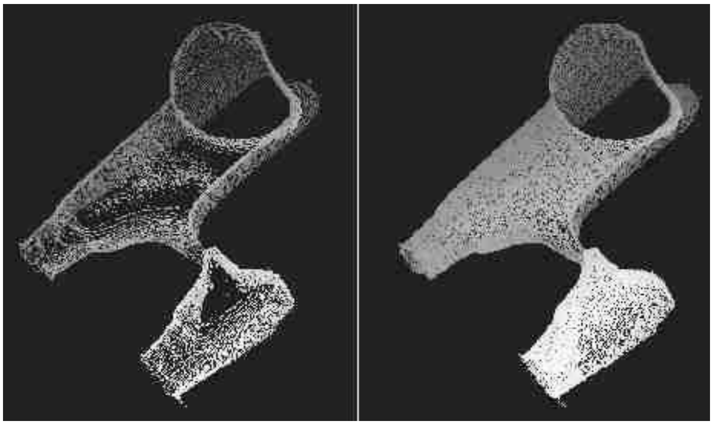

Fig. 6. Point cloud [19].

A special aluminum research block was made in order to compare the measuring possibilities of coordinate measuring devices. The object of the investigations was a cube with side width of 20mm and three holes with diameters of 3, 4 and 5mm and also with internal spherical surfaces with the diameter of 4mm. End face of the cube was milled with different angles and non-through pocket was also milled (Fig. 7).

a) b)

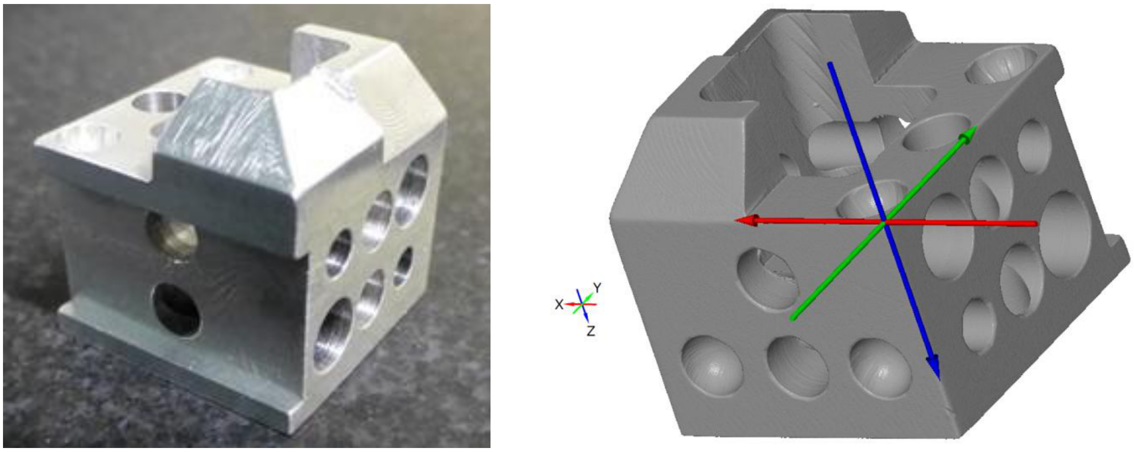

Fig. 7. Aluminum research cube: a) photograph, b) CAD model with the coordinate system of part.

The cube was investigated with the use of the DEA Global Image Clima 7.7.5 coordinate measuring machine and the GOM Atos II optical scanner at the Poznan University of Technology. Next the cube was measured with the application of the ZEISS Metrotom 1500 industrial CT scanner at the Wroclaw University of Technology. The same coordinate system of the part was defined for each case of the measurement. This fact allowed for rapid comparison of the measurement methods and for determining the system based on the same geometrical elements of the cube (Fig. 7).

Contact measurement with the use of CMM can be done in impulse and scanning mode. In practice, depending on requirements, time and CMM equipment we can get an information on the measured object from several or more cross-sections with different concentration of measuring points. This fact causes some lacks in information which in consequence can lead to omitting the maximum deviations of the measured feature. Optical scanner is better than

CMM in respect of the description of the measured surface. Optical scanner allows for measuring the entire surface even for the elements with very complex shapes. Measuring accuracy for this device depends on the applied optical system and resolution of measuring matrix. The limitation for the optical scanner is a lack of the measurement possibility of internal surfaces (e.g. deep holes and grooves) and lower measuring accuracy than for CMM. Such problems are not present during the measurement with the application of industrial CT scanner. This device allows for measuring both external and internal surfaces. In case of CT, a size of part and the ability of radiation absorption are the limitations. For large size objects, a CT scanner with higher power should be applied, but this leads to the decrease of the measuring accuracy.

The measurement results of several characteristic features of the examined cube were compared in order to check the measurement possibilities of CMM, optical scanner and CT scanner. After having defined the coordinate system (Fig. 7), the positions of three holes and their parallelism were estimated. Next the position and diameter of the half of internal sphere were evaluated. Three planes were also estimated, i.e. their mutual angular position and flatness.

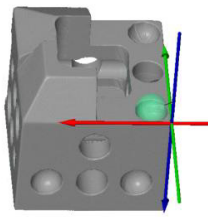

Table 1. Position and diameter of a sector of the internal sphere.

	Nominal value [mm]	Measured value [mm]	Deviation [mm]
CMM	X = 2.5 Y = 2.5 Z = 0.0 Ø = 4.0	X = 2.502 Y = 2.501 Z = -0.012 Ø = 4.259	X = 0.002 Y = 0.001 Z = -0.012 Ø = 0.259
Optical scanner		X = 2.529 Y = 2.512 Z = -0.058 Ø = 4.252	X = 0.029 Y = 0.012 Z = -0.058 Ø = 0.252
CT scanner		X = 2.515 Y = 2.505 Z = -0.062 Ø = 4.265	X = 0.015 Y = 0.005 Z = -0.062 Ø = 0.265

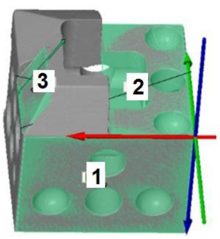

Table 2. An angle between planes 1-2 in plane Y-Z and planes 2-3 in plane X-Z.

	Nominal value [°]	Measured value [°]	Deviation [°]
CMM	α 1-2 = 90.0 α 2-3 = 60.0	α 1-2 = 90.048 α 2-3 = 59.690	α 1-2 = 0.048 α 2-3 = -0.310
Optical scanner		α 1-2 = 90.057 α 2-3 = 59.881	α 1-2 = 0.057 α 2-3 = -0.119
CT scanner		α 1-2 = 90.057 α 2-3 = 60.008	α 1-2 = 0.057 α 2-3 = 0.008

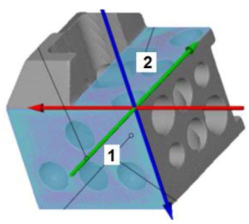

Table 3. Flatness of planes 1 and 2.

	Nominal value [mm]	Measured value [mm]	Deviation [mm]
CMM	Plane 1 = 0.0 Plane 2 = 0.0	Plane 1 = 0.010 Plane 2 = 0.012	Plane 1 = 0.010 Plane 2 = 0.012
Optical scanner		Plane 1 = 0.046 Plane 2 = 0.042	Plane 1 = 0.046 Plane 2 = 0.042
CT scanner		Plane 1 = 0.033 Plane 2 = 0.057	Plane 1 = 0.033 Plane 2 = 0.057

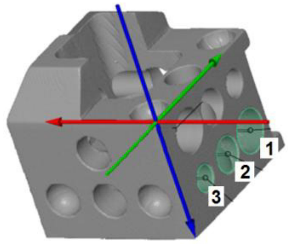

Table 4. Position of a circle which was calculated as the intersection of cylinders 1,2 and 3 with plane Y-Z.

	Nominal value [mm]	Measured value [mm]	Deviation [mm]
CMM	Cir1_Y = 15.0 Cir1_Z = 10.0 Cir2_Y = 10.0 Cir2_Z = 10.0 Cir3_Y = 5.0 Cir3_Z = 10.0	Cir1_Y = 15.006 Cir1_Z = 10.046 Cir2_Y = 9.996 Cir2_Z = 10.078 Cir3_Y = 4.986 Cir3_Z = 10.093	Cir1_Y = 0.006 Cir1_Z = 0.046 Cir2_Y = -0.004 Cir2_Z = 0.078 Cir3_Y = -0.014 Cir3_Z = 0.093
Optical scanner		Cir1_Y = 15.020 Cir1_Z = 10.065 Cir2_Y = 10.021 Cir2_Z = 10.074 Cir3_Y = 5.012 Cir3_Z = 10.111	Cir1_Y = 0.020 Cir1_Z = 0.065 Cir2_Y = 0.021 Cir2_Z = 0.074 Cir3_Y = 0.012 Cir3_Z = 0.111
CT scanner		Cir1_Y = 14.999 Cir1_Z = 10.040 Cir2_Y = 9.998 Cir2_Z = 10.045 Cir3_Y = 4.988 Cir3_Z = 10.080	Cir1_Y = -0.001 Cir1_Z = 0.040 Cir2_Y = -0.002 Cir2_Z = 0.045 Cir3_Y = -0.012 Cir3_Z = 0.080

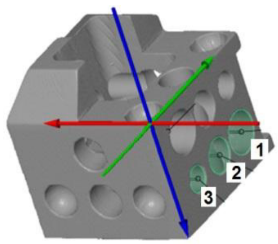

Table 5. Parallelism of holes 1-2 and 2-3.

	Nominal value [mm]	Measured value [mm]	Deviation [mm]
CMM	// 1-2 = 0.0 // 2-3 = 0.0	// 1-2 = 0.038 // 2-3 = 0.031	// 1-2 = 0.038 // 2-3 = 0.031
Optical scanner		// 1-2 = 0.047 // 2-3 = 0.042	// 1-2 = 0.047 // 2-3 = 0.042
CT scanner		// 1-2 = 0.046 // 2-3 = 0.036	// 1-2 = 0.046 // 2-3 = 0.036

5. Summary

The paper presents the measurement results for three different coordinate measuring devices. The estimation of different types of features was performed - this allows to look at the obtained values more widely. The measurements with the use of CMM were done in impulse mode, so each feature was measured at several points. In case of the optical scanner the measured object is covered with cloud of points - depending on the particular features the number of points is equal to several or dozens of thousands. However, the measurement of deep holes is a problem for the optical scanner, because there is a lack of some part of information. This problem does not exists for the measurement with the use of CT scanner. In case of our research, the applied CT scanner had a sufficient power for a full penetration of the measured object. This allowed us for full imaging of the geometry of both internal and external features. After converting the measurement results into the mesh of triangles, one can conduct the analysis in different measuring software packages, e.g. the GOM Inspect freeware which was applied for our investigations [20].

The obtained measurement results are converged - the maximum difference is equal to 0.05mm. The difference in the diameter of the internal sphere is equal to 0.013mm. This value is evaluated from the spherical surface only. The differences in the position of sphere centres are higher, and their maximum values for Z-axis are equal to 0.05mm. These values differ slightly for optical scanner and CT scanner, but for CMM these values differ considerably. This fact results from the low number of points describing the surfaces which were used during determining the coordinate system of the part. An angle between planes 1 and 2 is similar for all three devices, but an angle between planes 2 and 3 differs in a range of 0.32°. The flatness of planes 1 and 2 is characterized by much lower values for CMM than for optical scanner and CT scanner. This fact results from that these devices allow for measuring the entire surface, so the maximum peaks and valleys can be detected.

The measurement results of positions for three holes allow us to state that the highest deviations can be observed during the measurement using the optical scanner. This fact results from the above-mentioned and described problem of the measurement of holes with small diameters. In this case measuring data from CT and CMM allow to describe more precisely the cylinders as the entire unit. Similar situation can be observed during the measurement of position parallelism of these holes.

To sum up, we can conclude that these three types of coordinate measuring devices allow us for effective measurement of the element which has been presented in this paper. We cannot explicitly conclude which device is more appropriate to apply, because each of these devices is characterized by many advantages and drawbacks. Therefore, the authors intend to carry out further studies to verify the area of application of different types of coordinate measuring devices. The first step will be the performance of steel and polyamide blocks according to research presented in the article. This will allow to verify the effects of different absorption of X-rays on the result on computed tomography measurement. The next step will be to compare all three cubes of dimensions other features. The research plans and other work should help in the end to determine the accuracy and suitability of use variety of coordinate measuring devices, such as CMM, optical scanner and CT scanner.

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