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Studying the shape of solids of revolution with the use of optical coordinate metrology

Abstract

The optical methods of coordinate measuring are a tool that have been more and more frequently used in biometrological applications, due to their advantages. The object of this paper is to set the accuracy of modelling solids of revolution whose shapes and measurements find their application in medical diagnostics with the use of three measurement systems employing laser and structured light. The carry out the studies, a coordinate measuring machine LK CMM with LC60Dx laser scanner, a coordinate measuring Romer Absolute Arm 7320SI with HP-L-20.8 laser scanner and an optical Scan 3D Qualify scanner were used. The use of coordinate technique to analyze the shape of the model solids allowed for the comparison of accuracy of optical methods with reference to standards digitally modelled based in measurements made by CMM Leitz PMM 12106. The most preferable contactless system to render the shape of solids of revolution is the LK CMM with LC60Dx laser scanner.

Keywords: optical systems, measurements, standards, shape, accuracy.

1. Introduction

Optical coordinate metrology has been widely used in mapping the shapes of technical objects and in the non-invasive measuring of biological structures. Contactless measurement methods allow for the spatial representation of a shape based on data in the form of coordinate points identifying the surface. Digital methods are employed to create a 3D reconstruction of that surface [1-5]. An attempt has been made to establish a system for instant, comprehensive and accurate measurement tasks for bio-metrology, with the fastest of tasks being the field measurement techniques based on the projection of structured light on an object. However, they have their limitations, namely a low accuracy, the lack of standard procedures to evaluate the accuracy of measurements made with the use of those methods and the lack of efficient calibration methods and measurement coherence. Therefore, the accuracy of mapping the shape of standards of revolution has been assessed. The studies allow for the creation of an uncertainty model and the determination of the maximum value of a measurement error. The obtained results will allow to assess the practicability of those methods in medical applications.

In this paper, three measurement systems are presented. They employ a laser and structured light while scanning an object as well as other systems and design solutions that allow for reliable coordinate measurements.

The studies were carried out at the Cracow's University of Technology Coordinate Metrology Laboratory accredited by PCA with the use of a coordinate measuring machine LK CMM by Nikon Metrology with LC60Dx laser scanner, a coordinate measuring Romer Absolute Arm 7320SI by Hexagon Metrology with HP-L-20.8 laser scanner and an optical Scan 3D Qualify scanner by Smarttech 3D.

The objective was to determine the accuracy of mapping the shape of model solids of revolution with the use of optical coordinate metrology.

2. Material and methods

The following standards of revolution served as the material for the studies: a cylinder-cone model and a hemisphere-half-sphere model made of acrylonitrile butadiene styrene (ABS) polymer used to establish the procedure of assessment of the accuracy in mapping the shapes of medical objects (Fig. 1).

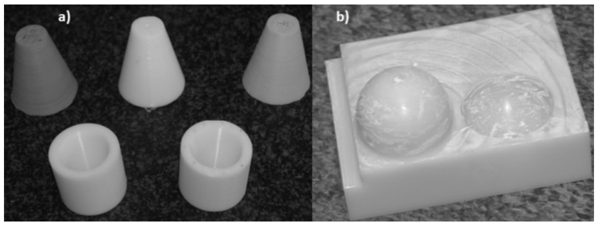

Fig. 1. Study models: a) cylinder-cone, b) hemisphere-half-sphere

Similar solids of revolution modelled volumetrically with the CAD software based on the measurements with the reference coordinate measuring machine WMP Leitz PMM 12106 (MPE=(0.8+L/1000) μm) in use by the Coordinate Metrology Laboratory served as the reference models [6] (Fig. 2).

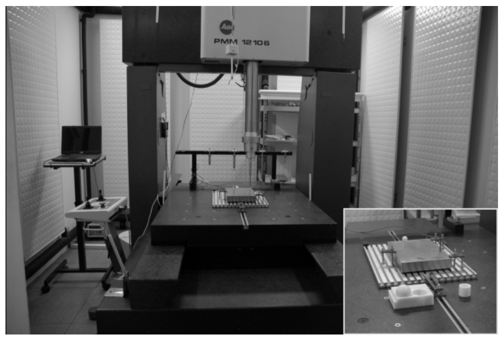

Fig. 2. Measurement of geometrical parameters of the study models with the Leitz PMM 12106 coordinate measuring machine

The methodology of the studies consisted in making a series of measurements of the solids of revolution with the use of three coordinate metrology systems and the spatial reconstruction of those objects based on a cloud of coordinate points in a software dedicated to a particular measurement system. Based on the measurements of each solid, their digital representations were compared to the reference solids modelled with the CAD 3D system using the best fit method (Fig. 3).

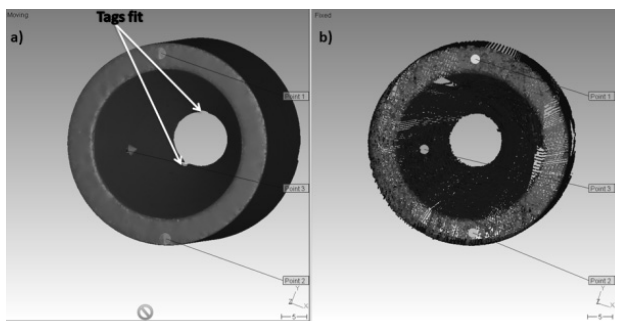

Fig. 3. Procedure of adjusting the shape of the cylinder-cone standard model: a) the reference model obtained with the Leitz PMM 12106 coordinate measuring machine, b) the model obtained with the assessed measurement system

The coordinate measuring machine LK CMM by Nikon Metrology with the laser triangulation scanner LC60Dx also by Nikon Metrology was the first measurement system used (Fig. 4).

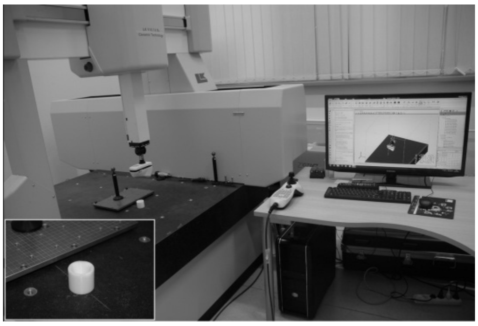

Fig. 4. Measurement with the LK CMM with LC60Dx laser scanner in Focus software

LK CMM with LC60Dx laser scanner is a stable, portal-like structure. It comprises a ceramic bridge and a granite table, due to which the effect of the temperature gradient on the accuracy of measurements is limited. Incremental systems serve as measurement standards. The structure of the machine is stabilized by airbags and the moving parts feature air bearings. The measurement range is 1000 mm × 1000 mm × 800 mm and the precision, as provided by the manufacturer, is MPE = 1.5 μm + L/375. The optical LC60Dx laser scanner that employs the principle of calculating the distance by triangulation is connected to the measuring machine. The basis for calculating the distance between the measurement object and the head of the scanner is the system of the right triangles. A beam of light projected by a laser diode on the measurement object, having passed through the optical system, is formed through a line beam. The image of the line is recreated by another optical system on a photo ruler. When the distance between the head and the surface of the measurement object changes, the image of the line moves along the photo ruler which serves as the standard distance. The parameters of the scanner was as follows: the width of the laser beam: 60 mm, the resolution: 0.060 mm, the accumulation of points 75000 pts./s, the head's error 0.009 mm (Fig. 4). The accuracy of the system was affected by the accuracy of the employed measuring machine and the laser scanner as well as the used data acquisition and 3D modelling software.

Another device used to make measurements within the studies was the coordinate measuring Romer Absolute Arm 7320SI by Hexagon Metrology with HP-L-20.8 laser scanner [7-9] (Fig. 5). A coordinate measuring arm (CMA) is a device that may perform both contact and contactless measurements. This device is mobile, manual and redundant. It comprises seven rotation pairs out of which four feature a full 360° rotation. Each pair is equipped with a disc angle measurement system (an absolute encoder).

Fig. 5. Measurement with the Romer Arm 7320SI with HP-L-20.8 laser scanner in 3D Reshaper software

For measurements there was used a contactless laser triangulation scanner with the following parameters: class II, working distance: 180±40 mm, linear frequency: 100 Hz, the line width: 104 mm, a minimal gap between the points: 0.013 mm, the error of the Probing scanner system: 0.009 mm, the error of the scanner-dispersion system: 0.036 mm, the accumulation of points 150000 pts./s. The parameters of the 7-axis arm with an integrated scanner were as follows: the measurement range: ±1000 mm, the spatial repeatability: ±0.061 mm, the precision of the scanning system: 0.079 mm.

The measurement procedure consisted in observing the projection of the laser spot on the measurement surface with CCD image sensors that served as detectors of the light intensity and in data acquisition in the adopted reference system [2, 10, 11]. The accuracy of the system was affected by: the laser scanner, the arm and the system for processing of the point cloud employed during measurements [12-17].

Research cycles consisted in the acquisition of data represented as a point cloud and its optimization through the elimination of distant points, filtration, triangulation and smoothing. As a next step, characteristic geometrical values were calculated [18, 19]. The measured object surface reflectance highly affected the quality of the measurement. The best results were obtained with matt surfaces. Shiny surfaces were covered by special powders in order to reduce their reflectance.

Another measurement technique used in the study was fringe projection that allowed for obtaining a full information about the surface of the measured object with the use of the optical Scan 3D qualify scanner by Smarttech 3D (Fig. 6). The system comprised a rotation table that allowed for the measurement of the whole object by putting together particular scans taken every 60° in a complete image. The method employed structured light in the form of a projection of raster or its sequence. The deformation of raster was recorded and then analysed with the discrete phase change method. Data processing, in order to obtain the real surface, consisted in setting the phase and scaling.

Fig. 6. Measurement with the Scan 3D qualify optical scanner in PCdmis Reshaper software

Imaging with that system consisted in the analysis of deformation of black and white rasters on the studied surface. The frequency of data acquisition was 2 MHz, which eliminated the effect of ambient oscillation and enabled to carry out dynamic studies. The studies were carried out for the field of view of 400 mm × 550 mm and 260 mm × 190 mm, the precision of measurements, provided by the manufacturer, was 0.07 mm.

The Scan 3D qualify scanner measured the deformation of structured white light on the surface of the object subjected to measurement in the whole field of view at the same time [4, 20-22]. The following scanning techniques were used: the Gray code and phase shift. As a result, a point cloud was obtained. Due to those techniques, the determination of localisation of points in the measurement space was possible. The uncertainty of measurement was caused by: wrongly determined parameters of the projector-detector system, thermal instability, lighting, the distance between the projector and the detector. The accuracy of the measurement was 0.08 mm. A high precision and resolution of the measurement as well as its automation were the key advantages of the system.

Regardless of the measurement system the process of data analysis was identical. It consisted of collecting data in the form of point cloud coordinates. Further processing comprised the elimination of areas that were significantly different from the totality of the obtained results, the filtration within which noises were eliminated as well as the reduction of artefacts. Following the data optimization, the coordinate system was determined. The point cloud was subjected to triangulation – as a result, a surface mesh model was obtained.

The research strategy in the aforementioned systems involved the performance of 20 measurement cycles that allowed to obtain the image of the whole scanned structure. The number of measurement passages was due to the imaging method and the adopted software for analysis.

The following computer software were used: WMesh 3D, 3DMax, ProEngineer, Poly Works, Catia, Geomagic Studio 2012.

3. Results and discussion

Geometrical parameters of the study models were determined through a series of 10 measurements (for each model) on a coordinate measuring machine. The mean dimensions of the models were as follows: for the cylinder-cone – cylinder diameter of ø35.082 mm, cylinder height of 35.163 mm, cone characteristic diameters of ø25.024 mm and ø12.035 mm, cone height of 35.126 mm (Fig. 1a); for the hemisphere-half-sphere – ball radius SR 17.513 mm, ball angle of flare of 180°, dome radius SR of 17.618 mm, dome angle of flare of 160° (Fig. 1b). The standard deviation was s=0.004 mm. Based on the measurements made with the coordinate measuring machine Leitz PMM 12106 the reference models generated with the CAD software for the selected standards were determined.

Digital study models obtained from three measurement system employing the laser and structured light were compared to relevant reference models in 3D Reshaper.

The errors in mapping the shape arising from the comparison of the models obtained with the coordinate measuring machine LK CMM with LC60Dx laser scanner to the reference models are contained in the following ranges: for cylinder-cone from +1.000 mm to +0.175 mm for 1.35%, from +0.175 mm to –0.135 mm for 94%, from –0.135 mm to –0.325 mm for 2.15%, from –0.325 mm –1.000 mm for 0.86%; for hemisphere-half-sphere from +0.300 mm to +0.150 mm for 5.6%, from +0.150 mm to –0.037 mm for 60%, from –0.037 mm to –0.075 mm for 7.66%, from –0,075 mm to –0.155 mm for 9.28%, from –0.155 mm to –0.300 mm for 11.8%. For the cylinder-cone model 98.5% of deviations ranged between +0.155 mm and –0.110 mm. For the hemisphere-half-sphere model the maximum deviations occurred around the apex of the ball surface, which may indicate the effect of human errors. In this measurement system, around 13% of non-measured areas were observed. For the cylinder-cone model negative deviations accounted for 99%, and positive ones – 0.5% (Fig. 7).

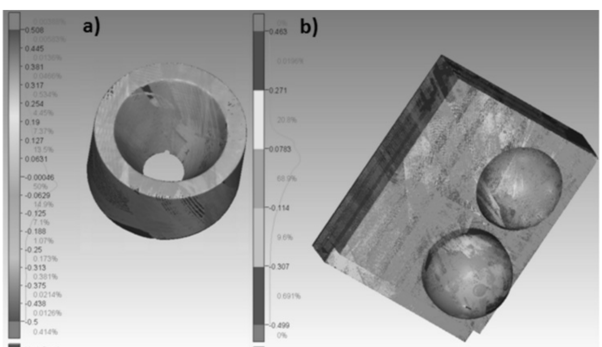

Fig. 7. Distribution of errors in mapping the shape for measurements with the LK CMM with LC60Dx laser scanner of the following models: a) cylinder-cone, b) hemisphere-half-sphere

The errors in mapping the shape arising from the comparison of models obtained with the WRP Romer Arm 7320SI with HP-L-20.8 laser scanner to the reference models are contained in the following ranges: for cylinder-cone from +0.505 mm to +0.254 mm for 0.6%, from +0.254 mm to +0.127 mm for 11.82%, from +0.127 mm to –0.063 mm for 63.5%, from –0.063 mm to –0.188 mm for 22%, from –0.188 mm to –0.500 mm for 0.82%; for hemisphere-half-sphere from +0.200 mm to +0.114 mm for 8.5%, from 0.114 mm to –0.057 mm for 75%, from –0.057 mm to –0.114 mm for 7.5%, from –0.114 mm to –0.171 mm for 3%. For the cylinder-cone model 88% of deviations ranged between +0.020 mm and –0.188 mm. The maximum values of deviations occurred in places where the movement of the head had changed as well as on the cone surface. Artefacts occurred mainly on the cone surface and the cylinder surface that were in contact with the table of the machine. For the hemisphere-half-sphere model the maximum deviations occurred on the so called scanning poles situated at the apex of the ball. The minimum deviations and artefacts occurred on the ball surface whose tangent was perpendicular to the surface of the table. For the measurement with the WRP Romer Arm 7320SI with HP-L-20.8 laser scanner positive deviations accounted for 47%, and the negative ones for 52%. The remaining part of the surface was not defined by the measurement system (Fig. 8).

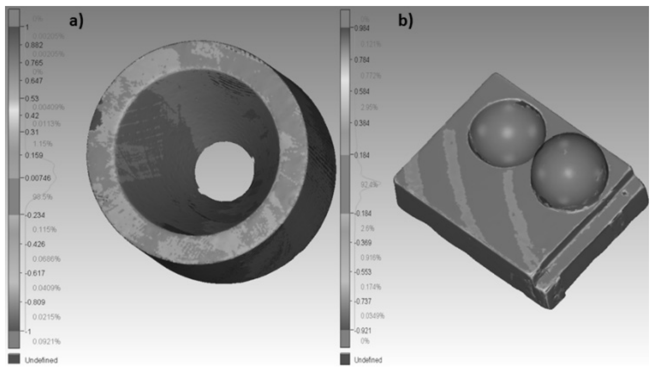

Fig. 8. Distribution of errors in mapping the shape for measurements with the WRP Romer Arm 7320SI with HP-L-20.8 laser scanner of the following models: a) cylinder-cone, b) hemisphere-half-sphere

The errors in mapping the shape arising from the comparison of the models obtained with the Scan 3D qualify optical scanner to the reference models are contained in the following ranges: for the cylinder-cone from +1.000 mm to +0.417 mm for 0.24%, from +0.417 mm to –0.167 mm for 57.7%, from –0.167 mm to –0.750 mm for 13.8%, from –0.750 mm to –1.00 mm for 12.8%; for hemisphere-half-sphere from +0.3 mm to +0.060 mm for 9.85%, from +0.060 mm to –0.060 mm for 83%, from –0.060 mm to –0.180 mm for 6.55%, from –0.180 mm to –0.300 mm for 0.25%. For the cylinder-cone model 70% of deviations ranged between +0.400 mm to –0.250 mm. For the cylinder-cone model the areas of positive deviations significantly different to deviations in adjacent areas – given that the shape of the studied surface was maintained – may be deemed artefacts arising from the measurement method. For the hemisphere-half-sphere model the maximum values occurred at the apexes of the studied surfaces. The ring-like distribution of areas with similar deviations as well as undetermined areas was a characteristic feature.

The standard deviations from the series of measurements were: for the coordinate system of the LK CMM with LC60Dx laser scanner: 0.051 mm, for the coordinate measurement Romer Absolute Arm 7320SI with HP-L-20.8 laser scanner: 0.069 mm, and for the Scan 3D qualify optical scanner: 0.072 mm without the rotation of the table, and 0.098 mm – with the rotation of the table, respectively (Fig. 9).

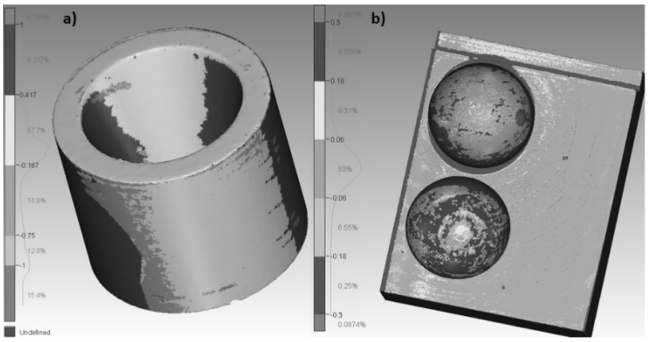

Fig. 9. Distribution of errors in mapping the shape for measurements with Scan 3D qualify optical scanner of the following models: a) cylinder-cone, b) hemisphere-half-sphere

Contactless measurement methods are very helpful in mapping the shapes of biological structures, both solid and soft. Those structures feature a complex 3D geometry, therefore, mapping their shapes requires the identification of coordinates of a large number of points describing those surfaces. As tissue structures contain 60-97% of water, the change in their shapes and dimensions may occur as a result of the loss of water during the study. All study systems should combine a fast accumulation of points with a high level of accuracy [23].

Also, the device's user-friendliness and functional availability are very important. The use of special optical systems may be the answer to such a need as they are able to identify a large amount of data within a short time. They also allow carrying out a real-time assessment of the shape. The studies referred to in this paper show the practicability of the optical coordinate technique in mapping the shapes of solids of revolution.

Establishing a measurement technique adapted to particular shapes and research requirements was the priority of the studies described herein. The studies allowed comparing the accuracy of contactless measurement methods to standards created with the use of contact coordinate measuring machines.

4. Conclusions

Based on the studies carried out with the use of three measurement systems, different characteristics of distribution of errors in mapping the shapes arising from the shapes of models were reported. The measurement errors become bigger as the angle between the studied surface and the scanning plane gets bigger.

For systems employing laser scanners the following were observed:

- For the cylinder-cone model – the occurrence of 90-92% of negative deviations as well as relatively small (3-5%) unidentified areas situated at random.
- For the hemisphere-half-sphere model – the occurrence of both positive and negative deviations as well as the occurrence of unidentified areas situated in the adopted coordinate system, on the ball surface at the distance of $z<6$ mm from xy plane.

For the system employing structured light the following were observed:

- For the cylinder-cone model – a characteristic band-like distribution of deviations, both positive and negative, as well as unidentified areas arising from a number of projections put together
- For the hemisphere-half-sphere model – the ring-like distribution of deviations both positive and negative with a clear localisation of poles of the maximum deviations.

In the analysed measurement systems, the most preferable contactless system for mapping the shape of solids of revolution is the coordinate measuring machine LK CMM with LC60Dx laser scanner.

In optical coordinate metrology, it is possible to create hybrid measurement systems through the use of the coordinate system related to the object based on contact coordinate measuring machines and then to make measurements with a contactless system in the same coordinate system.

Regardless of a number of papers on optical systems, the question of mapping the shapes still remains to be solved. This is due to a wide variety of biological structures in terms of material, a wide variety of optical systems as well as applicable data acquisition methods.

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