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ASSESSMENT OF FREE-FORM SURFACES' RECONSTRUCTION ACCURACY

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Abstract

The paper presents the problem of assessing the accuracy of reconstructing free-form surfaces in the CMM/CAD/CAM/CNC systems. The system structure comprises a *coordinate measuring machine* (CMM) PMM 12106 equipped with a contact scanning probe, a 3-axis Arrow 500 Vertical Machining Center, QUINDOS software and Catia software. For the purpose of surface digitalization, a radius correction algorithm was developed. The surface reconstructing errors for the presented system were assessed and analysed with respect to offset points. The accuracy assessment exhibit error values in the reconstruction of a free-form surface in a range of ± 0.02 mm, which, as it is shown by the analysis, result from a systematic error.

Keywords: reverse engineering, accuracy assessment, free-form surface, coordinate measuring machine, radius correction

1. Introduction

The measurement method based on CMM technology has found widespread use in those areas of industry which require high accuracy and reliability of measurement, or to which other methods cannot be applied due to the nature of measurement, *e.g*. in measuring free-form surfaces within the scope of industrial design. In this case, an initial design of such products is entrusted to craftsmen who construct the first physical model (a reference object) of the structure of a designed product. Naturally, the design consists of far more complicated forms than simple regular shapes – such as spherical, cylinder, or conic ones – which are not explicitly described in mathematical terms. The subsequent stages of design involve making a digital cloud of points of the reference object and creating a prototype from a material suitable for manufacturing of, *e.g*., injection moulds. For this purpose, it is necessary to create an integrated system comprising tools for measurement, analysis, and manufacturing. These issues fall within the area of widely-understood *reverse engineering* (RE) [1, 2].

In this process (RE) errors not only result from many factors related to digitizing, CAD/CAM modelling, and manufacturing processes (CMM/CAD/CAM/CNC), but also are being induced by the applied machine tools and measuring strategies. This problem has been comprehensively analysed in many papers [3–6].

The paper focuses on presentation of a method developed for creating a free-form surface of a reference object, along with its digitizing using a coordinate measuring machine (CMM). Next, it creates a free-form surface copy and evaluates reconstruction errors of the CMM/CAD/CAM/CNC system (Fig. 1).

The digitizing process was carried out with a CMM equipped with a contact scanning probe. A surface made of aluminium (AlZnMgCu0.5) was examined. For the purposes of the described

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system, a method including software for probe tip radius correction in reference to free-form surfaces was developed. The applied procedure is shown in Fig. 1.

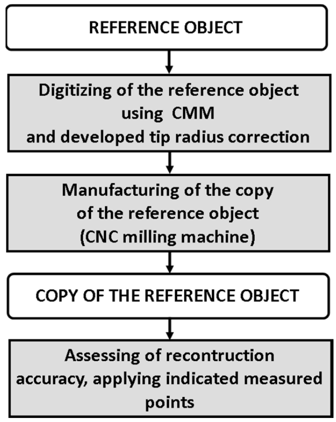

Fig. 1. A workflow of the proposed procedure.

The paper does not put emphasis on analysing the impact of individual error-inducing factors on the final results, treating the system as a whole. The obtained results, therefore, should be perceived as attainable accuracy of the presented CMM/CAD/CAM/CNC system used for the reconstruction of a free-form surface from readings taken from a reference object.

2. Probe tip radius correction and measurement strategy

Coordinate measuring machines with contact scanning probes enable to inspect practically any free-form surface. Admittedly, their capability of continuous-contact scanning with the highest possible degree of accuracy offer a huge advantage. However, the key issue that needs to be tackled in the context of free-form surfaces is radius correction of an indicated measured point set in the centre of stylus tip in relation to the corrected measured point (Fig. 2). Since a measured surface lacks a mathematical representation, determination of the tip correction vector will always bound to be approximate, *i.e.* encumbered with an error.

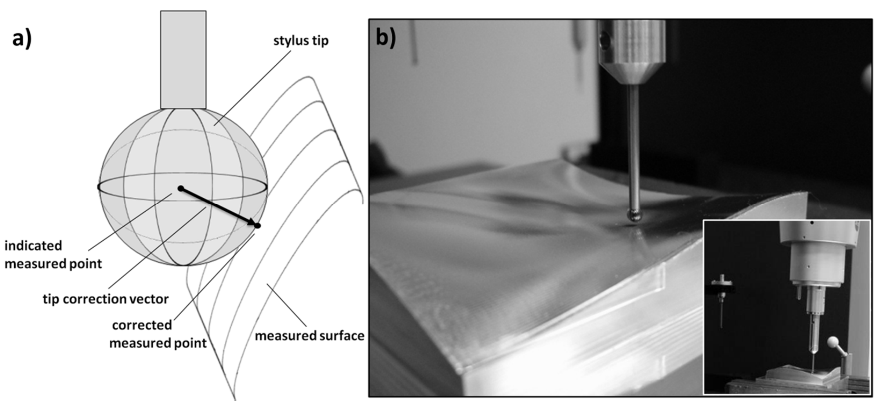

Fig. 2. The idea of coordinate measurement; the principle of probe tip radius correction (a); measurement by means of CMM (b).

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This issue has been discussed at length in the literature. The methods of probe tip radius correction may be grouped into several areas. One of them is approximation of a cloud of points obtained from scanning a surface with the use of sets of mathematical formulas, most often B-spline functions or others [7]. This approach is commonly known as the least-squares method [8]. However, this leads to averaging the values of respective measuring points, which adversely affects the accuracy of the reconstruction of a measured surface. In another method of probe radius compensation there are determined normal vectors, drawn in the positions of neighbouring measuring points [9–11].

A fundamentally different approach has been offered by Wozniak *et al.*; they use an algorithm which does not calculate the probe tip radius correction vector, but directly determines adjusted measuring points. This approach is based on fuzzy logic algorithms [12] and a geometric method [13].

For the purpose of probe tip radius correction and finding a vector normal to the surface at a given point, it is possible to employ a method analysing force distribution in the transducer of an active probe head [14].

In order to avoid errors resulting from the probe tip radius correction in accuracy assessment on the basis of a CAD model, measurements can be performed without that correction. In this case the indicated measured points are compared with points distributed on an off-set surface in a stylus tip radius distance from the CAD model in the normal direction [15].

Taking into consideration that not every computer program running on CMMs has separate modules for probe tip radius correction in reference to free-form surfaces and bearing in mind that the tip radius compensation algorithm does not produce expected results, in this work a computer software used for probe tip radius correction has been developed. The input data for the presented stylus tip radius correction method is a grid of points (the indicated measured points) displaced from the reference object by a length of the stylus ball radius. The algorithm is based on determination of vectors starting from a given indicated measured point and pointing to all neighbouring points as well as being based on indication of a normal vector for each of the determined vector pairs. The normal vector is estimated by a mean vector determined from a bunch of vectors starting from an indicated measured point (Fig. 3). What provides a distinct advantage of the presented solution is that the selection of an appropriate measuring strategy ensures satisfactory results and may be used for any cloud of points grouped in the measuring paths.

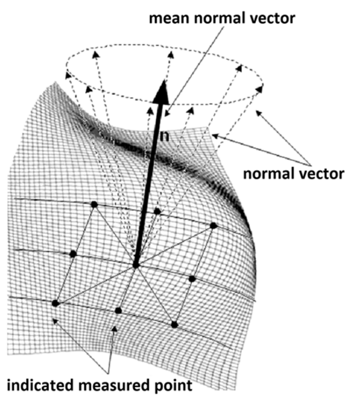

Fig. 3. The strategy of determining the direction of the probe tip radius correction vector.

With the view of verifying the developed method, a set of reference spheres with known diameters were measured. In the first place, the radii of the spheres and sphericity deviations were determined with the use of a coordinate measuring machine PMM 12106. The obtained values are compiled in Table 1. Then, the upper surfaces of spheres were scanned (a point density of 0.5 × 0.5 mm) using a scanning head with a tip radius of 1.5 mm. The indicated measured points were subjected to stylus tip radius correction. Each corrected measured point was compared with its corresponding point calculated using an analytical spherical function (partial derivatives). The distance between these points was regarded as an error of the correction method. Table 1 displays the average error values calculated for all the points. Verification of the method showed that it brought satisfactory results, especially for surfaces with a larger radius of curvature.

Table 1. The accuracy of the tip radius correction method [mm].

radii of the spheres [mm]	sphericity deviations [mm]	average error of the correction method [mm]
4.7631	0.0010	0.0120
7.1446	0.0011	0.0067
12.7007	0.0011	0.0046
17.4636	0.0008	0.0028
25.4015	0.0017	0.0017
50.0059	0.0023	0.0009

After analysis of the results, it may be inferred that an error of the presented probe tip radius correction method depends on the radius of curvature. Due to the fact that the radii of the measured surface curvatures were greater than the radius of the largest sphere and owing to a higher point density in the measuring path during scanning, it was concluded that the accuracy of the probe tip radius correction method was sufficient.

3. Accuracy assessment methodology of milled free-form surface reconstruction using developed probe tip radius correction method

3.1. System structure and tools

The examined system structure consisted of the following components (Fig. 4):

- a laboratory version of coordinate measuring machine PMM 12106 equipped with a contact scanning probe;
- a 3-axis Arrow 500 Vertical Machining Center fitted with ACRAMATIC 2100E control;
- a high-speed spindle TDM, enabling machining at a maximum speed of 40,000 rev/min (High Speed Cutting);
- software: QUINDOS, Catia.

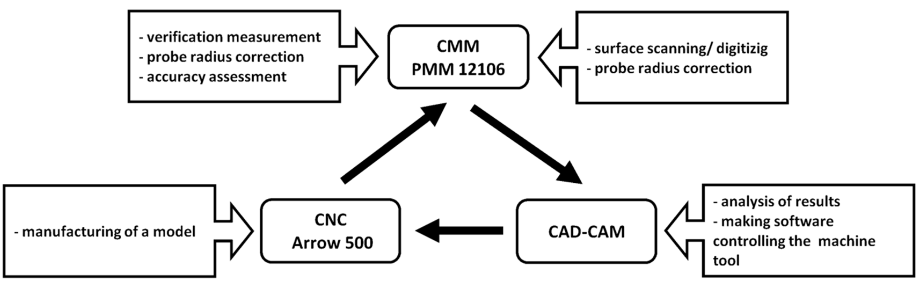

Fig. 4. The system structure.

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3.2. Digitizing and manufacturing

In order to test the adopted method, a surface containing concave and convex curvatures was used as the reference object. This object was treated as a material of standard size; the accuracy of reconstructed items was meant to be referred to it. The first step in research was to create a digital cloud of points of the reference object. It was made with the use of a coordinate measuring machine PMM 12106 equipped with a contact scanning probe. Measurement of the reference object was made in the continuous scanning mode. A distance between the paths was set to 0.5 mm, whereas a density of points in the path was set to 3 points/mm. The points which were obtained from surface scanning were subjected to the stylus tip radius correction, as it was described in Section 2 (Fig. 5). A length of the correction vector is the effective radius of the probe tip, which comes from a qualification procedure before measurement. When measurements were carried out with a contact probe terminated with a ball stylus tip, the measuring devices collected points separated with a fixed distance from the actual surface. The tip radius correction enabled to obtain corrected points representing actual (approximate) copies of the reference object surface, which became the basis for generating a machining program on a CNC milling machine. The copy of the reference object was manufactured using a monolithic ball-nosed milling cutter with a diameter of 8 mm, on a 3-axis Arrow 500 Vertical Machining Center fitted with ACRAMATIC 2100E control.

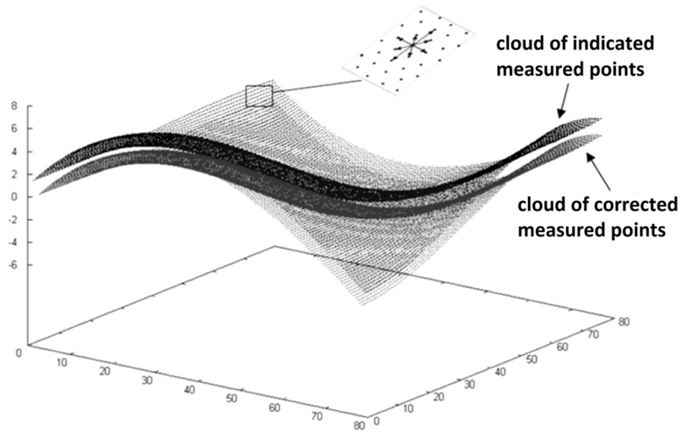

Fig. 5. Measurement of points before and after the probe tip radius correction.

4. Assessment of reconstruction accuracy

Regarding evaluation of the reconstruction accuracy, the indicated measured points obtained during digitization of the reference object copy were subjected to examination. The indicated measured points of the reference object were used as input points to control the measuring process of its copy. From a measurement point of view, it was recommended to probe the area in the normal direction. To determine the normal vector, the software dedicated to probe tip radius correction was used, which additionally calculated the normal versor for every single indicated measured point. Fig. 6 presents a window of the measuring mode from Quindos software.

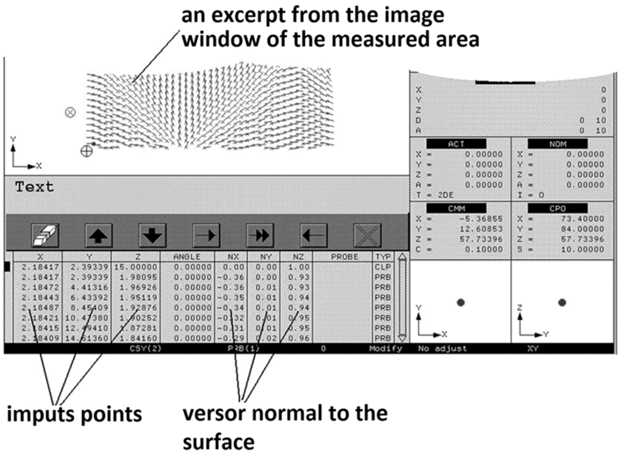

Fig. 6. A window of the measuring mode from Quindos software.

The input points (the indicated measured points from the reference object) were imported to Quindos metrology software cooperating with a CMM. The prepared input data, after setting the local coordinates, enabled to measure the reference object copy in the automated mode.

Comparison between the coordinates of points obtained from the performed measurements and the (input) measured points enabled to determine a map of errors. In the ideal case, measurement should be taken in the same point. In order to minimize the impact of stress change within the measured surface, a constant contact force in the vices of the machine tool and the measuring machine was applied. Fig. 7 shows graphical interpretations of reconstruction error calculation for each measured point.

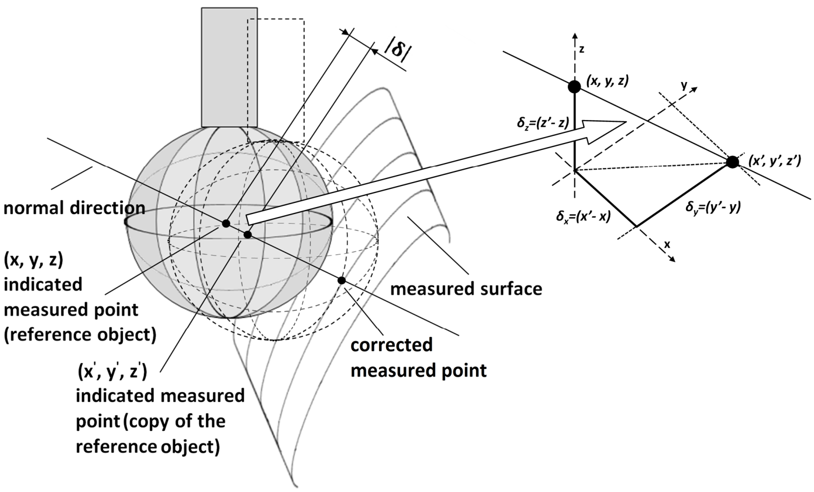

Fig. 7. The principle of determining a reconstruction error in a point.

A mapping error is determined by the following equation:

$$\delta = \big((x' - x), (y' - y), (z' - z)\big),$$
$$\delta = (\delta_x,\ \delta_y,\ \delta_z), \tag{1}$$

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where: δ – a reconstruction error in a point; $\delta_x, \delta_y, \delta_z$ – x, y, z error components; (x, y, z) – an indicated measured point of the reference object; (x', y', z') – an indicated measured point of the reference object copy.

According to the formula (1), the error values (δ_x, δ_y, δ_z) were calculated. Fig. 8 shows a spatial distribution of the individual *x, y, z* error components across the surface.

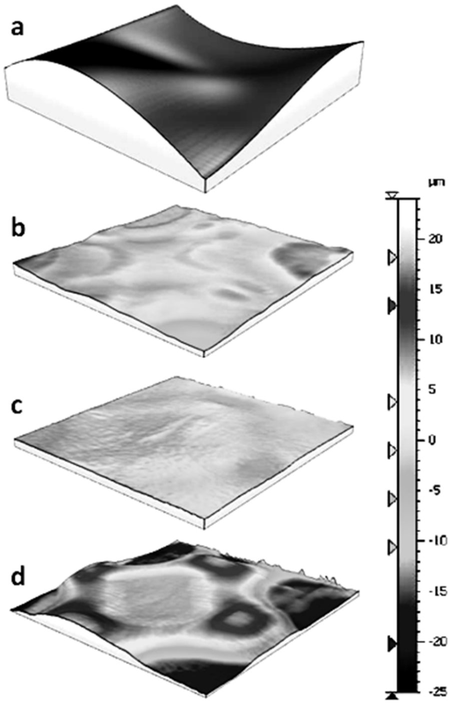

Fig. 8. Reconstruction errors [µm]: a 3D surface profile (a); the values of x component of the error (δ_x) (b); the values of y component of the error (δ_y) (c); the values of z component of the error (δ_z) (d).

From a preliminary analysis of the obtained results, it may be concluded that a significant share in a vector error value has its z component. Therefore, mainly this component was subjected to analysis in further research.

5. Analysis of errors in selected surface profiles

Further error analysis was carried out for selected profiles, characteristic for this surface. Fig. 9 shows the error values for the z component.

As it has been already mentioned, finding the origin of errors in such a complicated system as CMM/CAD/CAM/CNC is very complex. Errors result from a variety of factors which, if acting together, may add up or, which is even more difficult to capture, may compensate each other.

It may be expected, however, that if the measuring-manufacturing system is stable (repeatable), it will be generating errors of a specific character, dependent on the curvature of an analysed surface. In order to capture potential regularities, errors in selected (specific) cross-sections of the surface were analysed (Fig. 9). From the analysis of selected curvature profiles, it was concluded that if the cutter axis was perpendicular to the plane tangent to the surface, an error in the direction of z axis amounted to approx. +0.020 mm, (Fig. 9, Fig. 11a). The analysis also showed that this error decreased with increasing inclination of the plane tangent to the surface profile until it reached a value of 0 mm at the inclination angle of about 50° (Fig. 9, Fig. 11b). At a greater angle of inclination, the absolute error value increased again, taking negative values (Fig. 9, Fig. 11c).

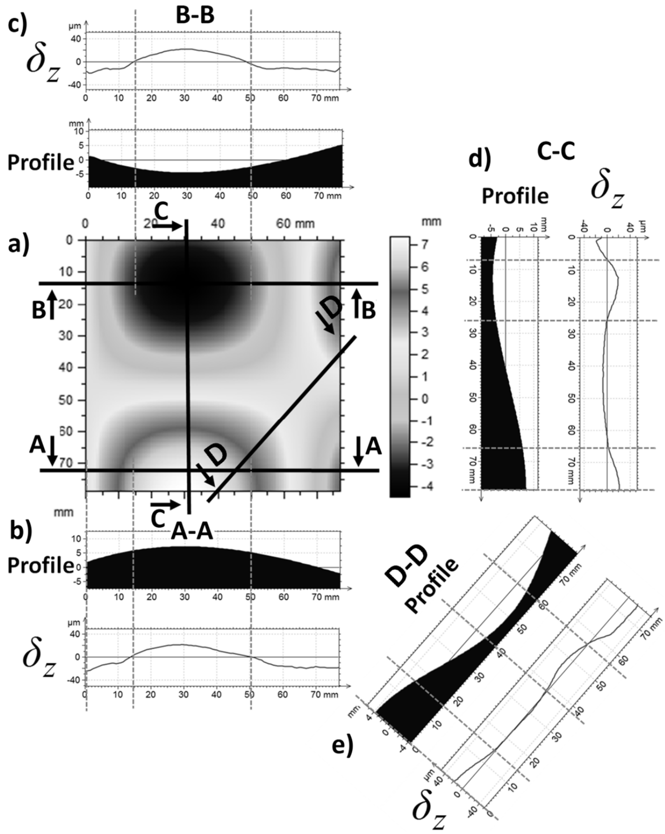

Fig. 9. The values of δ_z error components for respective surface profiles; the reference object (a); the profile and δ_z error components for the cross-sections: (A-A), (B-B), (C-C), (D-D).

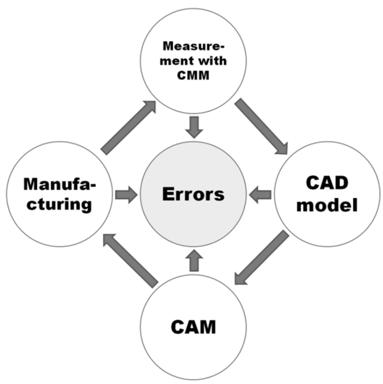

Fig. 10. The sources of surface reconstruction errors.

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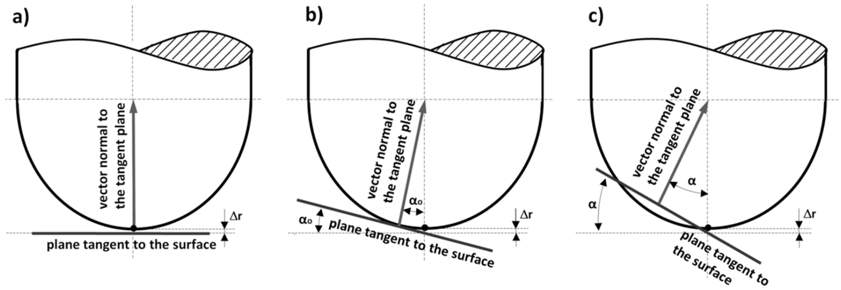

Fig. 11. The contact of the cutter with the machined surface.

A conclusion from the above considerations is that, if such a relationship reoccurs, it must be resulting from a strong (regular) factor, which in turn might be eliminated, *e.g*. at the level of software controlling the CNC machine.

6. Summary

The proposed method makes it possible to assess the reconstruction accuracy of complex-shaped products. It can be used along with the developed software as an effective tool supporting the work of constructors and technologists in designing and manufacturing of complex-shaped products limited by free-form surfaces (in RE).

The points in which measurement is performed result from scanning a reference object. An advantage of the proposed method is that there is no need to make another probe tip radius correction, which would contribute to further accumulation of errors. The probe tip radius correction is performed only once in order to manufacture a copy of the reference object. Regarding reconstruction accuracy assessment, both the indicated measured points obtained from scanning the reference object and normal versors are used, the latter calculated with the use of the developed correction method. The presented method was verified for a free-form surface reference object. The results showed that the reconstruction errors of the reference object exhibited values in a range of ±0.02 mm, which, as it is obtained from the analysis, resulted from a systematic error.

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