REVERSE ENGINEERING OF COMPLEX-SHAPE SURFACES

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Summary

The article presents issues connected with coordinate measurements of complex-shape surfaces. These measurements are presented on the example of carrying out the reverse engineering process of objects described with the use of free surface patches. The introduction to the article comprises a presentation of the B-spline method. This method has been applied to constructing geometric models of the reconstructed surfaces. Moreover, the introduction presents a method of constructing a surface patch on the basis of a cloud of points in space. Further in the article, a practical implementation of the methodology of reconstructing objects described with the use of complex shape surface patches has been presented. The methodology includes subsequent object measurements and reconstructing the object's geometric model, and concentrates on the possibly most accurate reconstruction of the shapes and dimensions of the researched object.

Keywords: complex-shape surface, coordinate measurements, reverse engineering

Inżynieria odwrotna powierzchni o złożonym kształcie

Streszczenie

W pracy przedstawiono zagadnienia pomiarów współrzędnościowych powierzchni złożonych. Pomiary prowadzono podczas realizacji procesu inżynierii odwrotnej obiektu opisanego za pomocą powierzchni swobodnej. Podano charakterystykę metody B-spline oraz sposobu budowy płata powierzchni na podstawie chmury punktów pomiarowych. Informacje te stosowano w tworzeniu modelu geometrycznego odtwarzanej powierzchni. Omówiono praktyczne zastosowanie metodyki realizacji procesu inżynierii odwrotnej obiektu określanego za pomocą płatów powierzchni o skomplikowanych kształtach. Przy użyciu tej metody prowadzono kolejne pomiary i rekonstrukcję modelu geometrycznego obiektu. Przyjęto kryterium dokładnego odwzorowania kształtów i wymiarów badanego obiektu.

Słowa kluczowe: powierzchnia o złożonym kształcie, pomiary współrzędnościowe, inżynieria odwrotna

Introduction

More and more importance is presently attached to the product quality, ergonomics and aesthetics. Application of coordinate measurements and CAD/CAM systems in industry creates great possibilities of integrating these two technologies [1, 2]. It exerts a vast influence on simplifying and shortening the phases of designing and manufacturing [3].

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Coordinate machines are widely used today and in many companies they often form an integral part of the whole machine park. Application of such machines is not restricted to quality control. They are also used to reconstruct objects of complex and unknown shapes [4].

It often happens that a stylist works on a product at the first stage of designing. The effect of their work may be a hand-made model made of a soft material, the shape of which is composed of many complex-shape surfaces. In order for the object to be manufactured and later to undergo different analyses, it is necessary to create its virtual model. Applying coordinate measurements offers the only chance to obtain such a model [5].

1. B-spline surfaces

Parametric methods of surface description are widely used in creating geometric models in CAD (computer-aided design) systems [6], with the B-spline method being one of the most popular. A B-spline surface (Fig. 1) is described with the use of two parameters, *u* and *v* [7].

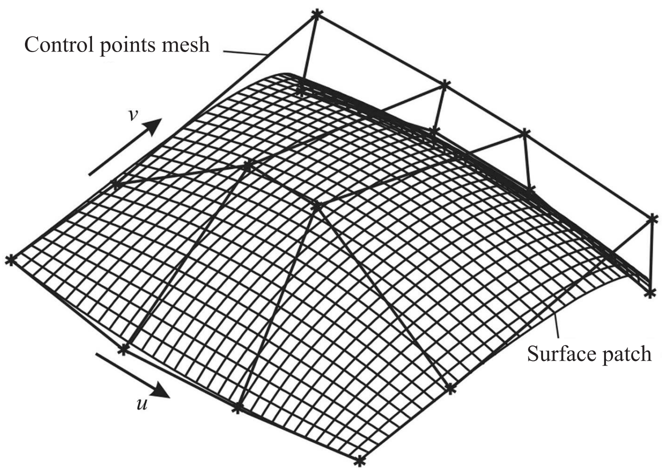

Fig. 1. B-spline surface patch

A mathematical representation of a B-spline surface is illustrated below [7]:

$$P(u,v) = \sum_{i=0}^{m}\sum_{j=0}^{n} D_{i,j} N_{i,k}(\mathrm{u}) N_{j,r}(v) \tag{1}$$

where: $D_{i,j}$ – vertices of the control mesh on which the surface is formed, $N_{i,k}(u)$, $N_{j,r}(v)$ – B-spline base functions.

Knowledge of this surface description method is vital because this technology is used to create surface models on the basis of a cloud of points which may be the result of coordinate measurements. The newest PC-DMIS software controlling coordinate measurement machines includes, among numerous object scanning methods, procedures of *UV* type surface scanning, i.e. scanning along the directions of the patch surface parameterisation.

The task to be solved during carrying out the reverse engineering process is to construct a geometric model of the reconstructed object [8]. The number and distribution of measurement points in this case greatly influences the choice of the method of creating the surface patch. One of the surface approximation methods, a method convenient to use with a uniform distribution of measurement points (Fig. 2a) takes the following course [9]:

- first, a series of curves located on the created surface patch is formed – these curves are approximated on subsequent rows of pre-set points located along one of the parameterisation directions, *u* or *v*; a series of isoparametric curves is obtained in this way (Fig. 2b),
- at the next stage, a surface patch is formed on the curve series (in the other parameterisation direction) (Fig. 2c).

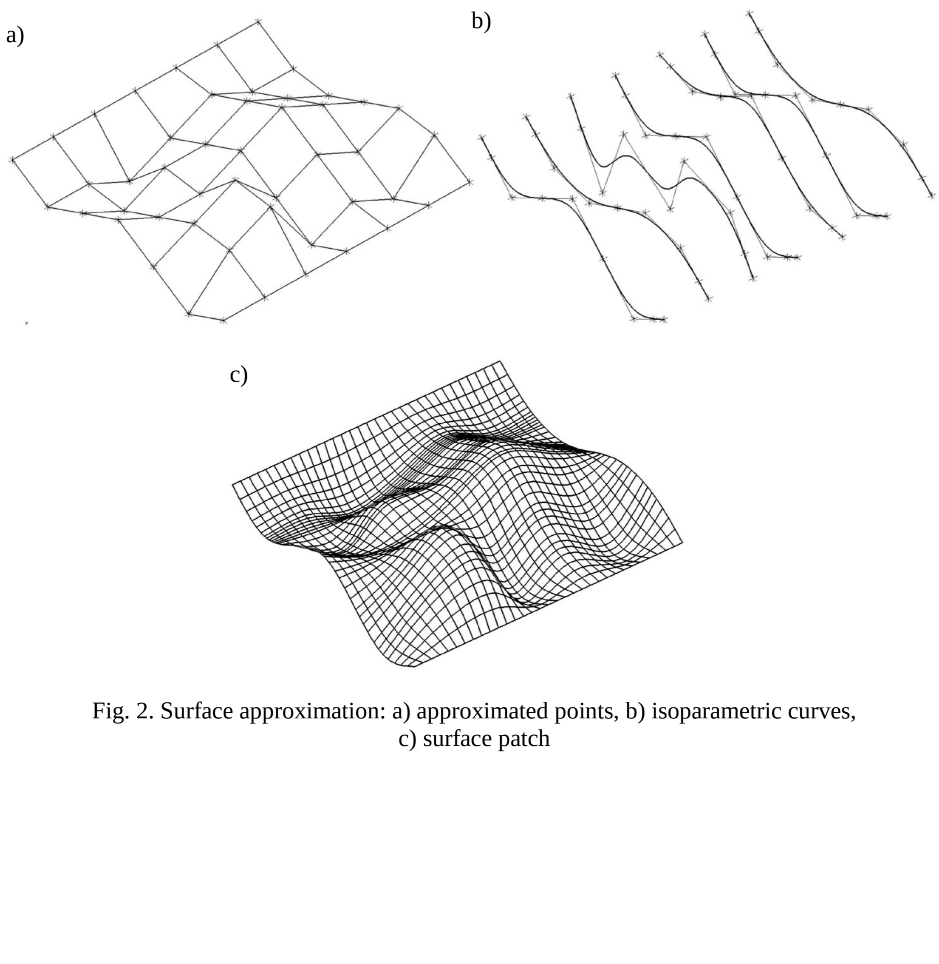

Fig. 2. Surface approximation: a) approximated points, b) isoparametric curves, c) surface patch

This method is effective in creating smooth surface patches. In the case where the created surface is a B-spline one, it is possible to model complex shapes on an extended cloud of points in space. The geometric model obtained in this way can be easily used further (e.g. in programming numerically controlled or coordinate measurement machines).

2. Methodology of reconstructing spatial objects

The suggested course of the process of reconstructing objects described with the use of free surface patches is illustrated in Fig. 3. Its aim is to create a geometric model of the reconstructed part. Such a model should be characterised by a high degree of accuracy with respect to its material form. The process of reconstruction is initialised by taking preliminary measurements. Due to the lack of the object's geometric model, these measurements are performed with the use of scanning techniques which require manual entering of information specifying the way in which the measurements are to be carried out (e.g. scanning range, scanning direction, etc.). This fact makes the object measurements more complex and longer; moreover, it limits the number of measurement points obtained in this way. After the preliminary measurement is finished, an initial geometric model of the reconstructed object is produced. Such a model is usually made with the use of the appropriate CAD software. Having the initially created geometric model, it is possible to use procedures of scanning the reconstructed object automatically, because on the basis of this model, information such as the scanning limits, the approach direction of the contact probe end, as well as the number and distribution of measurement points can be precisely determined [10]. The above advantages allow for fast and precise performing of control measurement with a high number of measurement points. Such measurement is needed to assess the accuracy of the created geometric model of the object with respect to its material form. If the accuracy of the geometric model is not satisfactory, the procedure is repeated. A new geometric model of the object is made on the basis of the last coordinate measurements, and the control measurements are repeated (it is possible then to control properly the number and distribution of measurement points). The

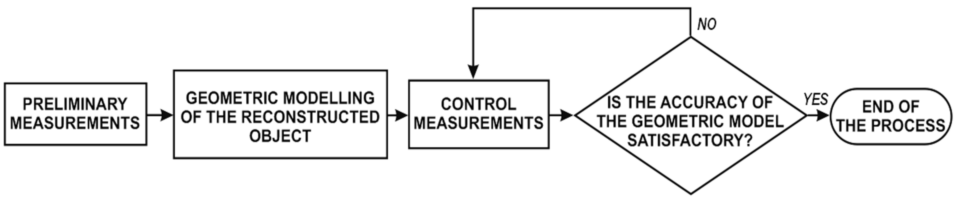

Fig. 3. Block diagram of reverse engineering process

process of reconstruction lasts until the moment when the accuracy of reconstructing the geometric model reaches an appropriate level when compared to the original.

The accuracy of the created geometric model of the object to its material equivalent was adopted as the measure of the accuracy of performing the reconstruction process. This measure was determined as the distance between a point observed during the measurement and the recently created surface model describing the object. This distance is determined in the normal direction to the obtained surface patch.

3. Performing the reverse engineering process of an object described with a free surface patch

Coordinate measurements of a complex-shape surface were taken on the example of the object shown in Fig. 4. The shape of the object was described with the help of a B-spline surface patch.

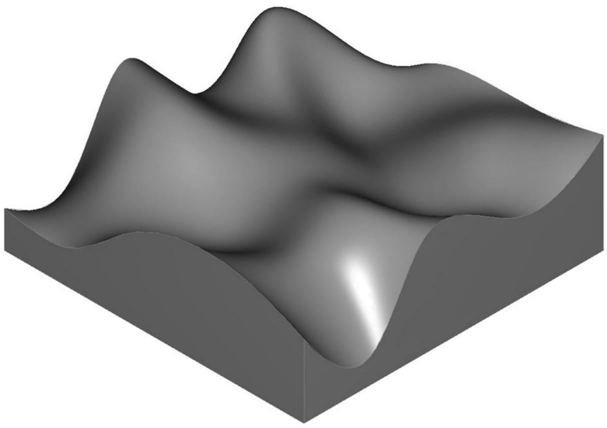

Fig. 4. Reconstructed object

The tests were carried out on a test stand comprising:

- a CNC milling machine,
- a PC class computer integrated with a coordinate measurement machine, with CAD/CAM (Mastercam) and measurement (PC-DMIS) software installed,
- Global Performance 070705 (Hexagon Metrology) coordinate measuring machine.

On this test stand, an object described with a help of a complex-shape surface patch was created in the first place. Pursuant to the procedure described above, a preliminary measurement of the reconstructed object was carried out.

Analysing the shape of the measured surface, the following assumptions had been made: the geometric model of the surface would be made with the use of one surface patch; in order to build it, a series of parallel curves constructed on the points obtained as a result of the measurement would be used. The object was scanned at subsequent parallel sections. The beginning, direction and end of scanning were indicated manually. The distance between the subsequent measurement points during scanning amounted to 4 mm, while the distance between the subsequent scanned sections was 10 mm. In this way, a cloud of measurement points was obtained, on which a series of B-spline curves was formed (Fig. 5a). The curves were then used for creating a preliminary surface model of the object (Fig. 5b).

a) b)

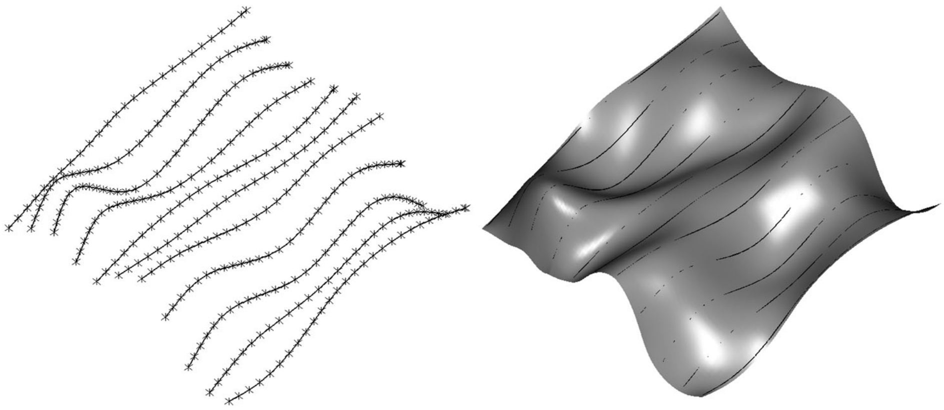

Fig. 5. Graphical representation of measurement results (a) measurement points and B-spline curves, surface patch (b)

It has to be emphasised here that indicating the scanning limits manually is rather a time-consuming and inconvenient process. The limitations of the linear open scanning technique stem from the very scanning method itself. In this method, the initial vectors of the probe end (Initial Vectors) were established by the system at the moment of contacting the probe end and the object manually. The PC-DMIS system determines the approach direction of the contact probe end to the measured surface at subsequent measurement points on the basis of the pre-set scanning growth and the last two measurement points (Fig. 6).

In the presented method, the measurement end approach to the measured object is not in the normal direction to the measured surface patch. It may result in an inaccurate determination of the compensation vector of the stylus end, which in consequence influences the accuracy of the performed measurement. The preliminary measurement aimed, above all, at obtaining data for constructing an initial geometric model of the reconstructed surface. Such a model becomes then a basis to carry out further object measurements.

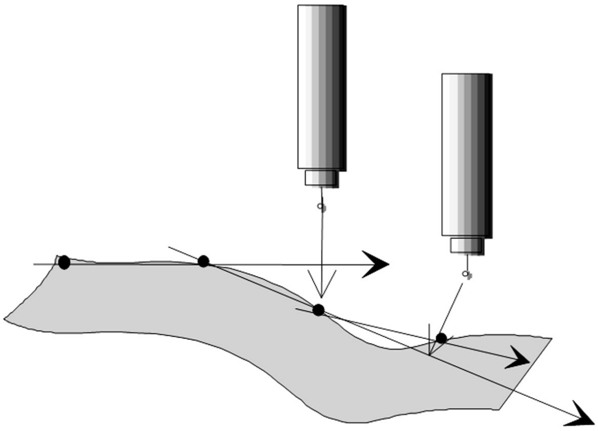

Fig. 6. Determining probe approach direction in linear open scanning

The advantages resulting from using a surface geometric model in coordinate measurements are as follows:

- the model includes information concerning the limits of the scanned object,
- the approach vectors of the probe end are generated in a normal direction to the measured surface,
- it becomes possible to use automatic measurement procedures of the reconstructed surface.

In subsequent measurements of the reconstructed object, the UVScan procedure offered by the PC-DMIS system was applied. This procedure (Fig. 7) is performed at the following order:

- indicating the measured surface (in a window of the PC-DMIS system),
- defining the scanning parameters (determining the *u* and *v* parameters range in which the surface measurement is to be performed, as well as the number of measurement points at each scanning direction),
- generating theoretical coordinate values of the measurement points and the approach vectors of the probe end (these parameters are determined on the basis of the object's geometric model).

The distribution of the measurement points and the scanning directions are presented on the measured surface in a graphical form (Fig. 8).

The scanning procedure adopted at this phase has the following advantages:

- allows to perform measurements with a much higher number of measurement points (which influences the accuracy of reconstructing the object),
- geometric model precisely defines the scanning limits and the approach direction of the probe end to the measured surface (thus, the compensation vector of the stylus end is determined more precisely).

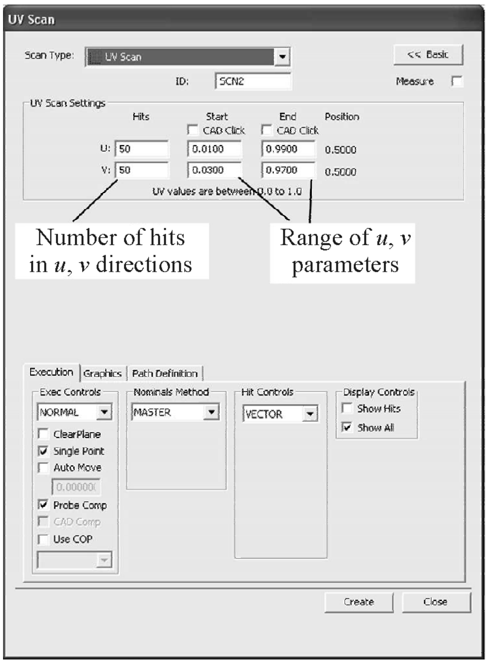

Fig. 7. UV scanning method window

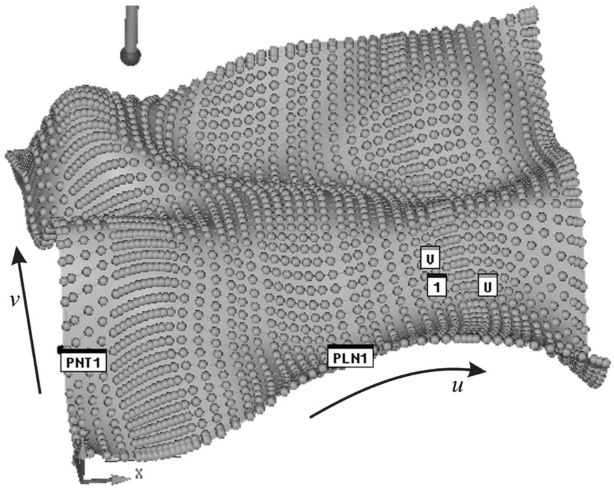

Fig. 8. Distribution of measurement points and scanning directions

After the first control measurement had been taken (with 2500 observed points obtained), the accuracy of reconstructing the object surface was estimated. At this stage, the data included in the programme controlling the performance of the measurement machine was used (information concerning the distance of the observed points from the surface of the geometric model used in the programme is included there). The reconstruction accuracy plot is shown in Fig. 9a. The biggest observed reconstruction error amounted to -1.172 mm. This value was highly unsatisfactory. According to the process diagram illustrated in Fig. 3, a decision was made to repeat the measurements.

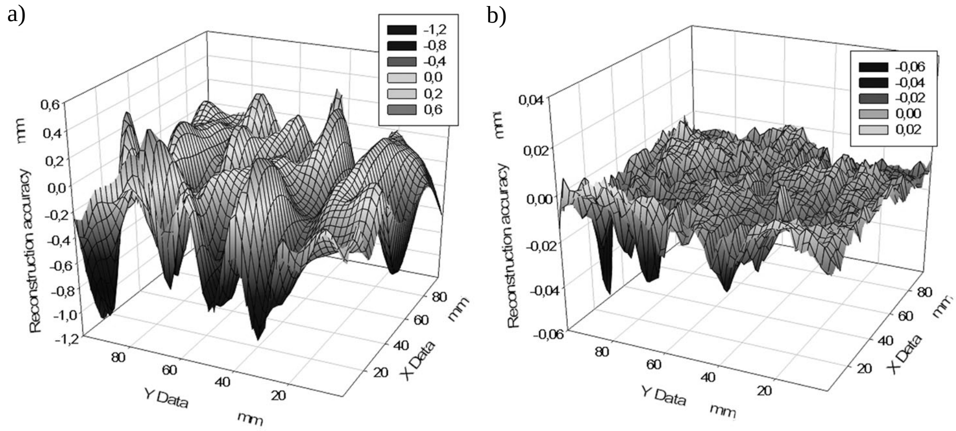

Fig. 9. Reconstruction accuracy: a) after preliminary measurement, b) after subsequent measurement

First, a new geometric model of the reconstructed surface was created. In order to build the model, the coordinates of the observed points, obtained in the previous measurement, were used. The measurements were performed with the use of the *UVscan* procedure presented earlier in this article. After another estimation, a significant increase in the accuracy of reconstructing the surface of the researched object was observed. The maximum observed error in this case amounted to -0.042 mm (Fig. 9b). This value was considered as satisfactory and the performing of the reverse engineering process was completed. Continuing the tested procedure, combined with increasing the number of measurement points, would influence further improvement in the accuracy of the created geometric model of the reconstructed object.

Conclusions

The present article describes a suggestion of applying an ‘iterated’ reverse engineering procedure to a complex-shape surface. It is characterised by a simplicity of performance and constant controlling of the accuracy of the created geometric model to its material original. The purpose of the initial measurements is to define the limits of the scanned area and to construct a surface patch on the basis of which the second phase of measurements is realised. At this phase, having the surface model of the reconstructed object, a greater freedom of selecting the distribution and number of the measurement points is possible. The approach directions of the stylus end are in this case generated more rationally, which contributes to the increase in the measurement accuracy. This procedure may be implemented at single fixing of the reconstructed object on the coordinate measurement machine table. Owing to this, the following measurement stages may be realised on the coordinate system which was defined only once. This fact has an impact on increasing the accuracy of object reconstructing. Applying B-spline surface patches allows for creating geometric models describing complex spatial shapes on the basis of a great number of points observed during measurements. The fact that procedures of automatic scanning of the reconstructed surfaces can be applied here, which greatly accelerates carrying out of the whole process, is not insignificant.

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Received in August 2010